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Diffuse–Source Salinity:
Mancos Shale Terrain

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Large areas of the Upper Colorado River Basin are underlain by saline geologic formations which contribute to the dissolved load or salinity of the Colorado River. The marine Mancos Shale is the most extensive saline formation outcropping in the Upper Basin and it is a major diffuse source of salinity. The soluble mineral content (SMC) of Mancos Shale can be as high as 20% but averages about 6% for areas of shale without interbedded sandstones. The major soluble mineral is gypsum.

The Mancos Shale is composed of three landform types: badlands, pediments, and alluvial valley floors. Pediments and pediment remnants are relatively stable landforms. Channel incision of alluvial valley floors can produce large quantities of sediment, however, salt contribution will be lower because alluvium has been leached and it has a lower SMC than in-situ Mancos Shale. Sediment and salt yield from badlands can be highly variable due to sediment storage and flushing effects, but overall erosion is rapid and runoff salinity is high. Experimental erosion studies on Mancos hillslopes reveal a positive relationship between salt production and sediment yield.

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DIFFUSE-SOURCE SALINITY
MANCOS-SHALE TERRAIN

Prepared for

BUREAU OF LAND MANAGEMENT

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by

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PREFACE

This report was prepared to review the literature on diffuse-source salinity associated with the Mancos Shale geologic formation. The Bureau of Land Management administers over one million of acres of saline soils within the upper basin states of the Colorado River drainage. The primary geologic formation associated with these saline soils is the Mancos Shale. The Mancos Shale and associated saline soils contribute dissolved solids to the Colorado River Basin, adding to the water quality problems of the River. Salt loading mechanisms include surface runoff and erosion, interflow, shallow ground water flow through streambed alluvium, and deep ground water flow.

The high salt loads of the Colorado River adversely affect more than 12 million people and over one million acres of irrigated land. This report emphasizes relationships between salt loading mechanisms and landforms within Mancos Shale regions, and reviews recent runoff, erosion, and salinity studies on Mancos Shale. It is intended to provide specialists and land managers information for use in land use planning, project design, and environmental assessment on Mancos shale.

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Finally, we acknowledge the use of an unpublished manuscript prepared in 1980 by Dr. J. B. Laronne of the University of the Negev, Israel. His report was prepared while he was receiving support from Office of Water Resources Research and Technology during sabbatical leave at Colorado State University.

Executive Summary

Large areas of the Upper Colorado River Basin are underlain by saline geologic formations which contribute to the dissolved load or salinity of the Colorado River. The marine Mancos Shale is the most extensive saline formation outcropping in the Upper Basin and it is a major diffuse source of salinity. The soluble mineral content (SMC) of Mancos Shale can be as high as 20% but averages about 6% for areas of shale without interbedded sandstones. The major soluble mineral is gypsum.

Determining the SMC of weathered shale or alluvium samples may require modification of standard procedures because of the slow dissolution rate of gypsum. A method is suggested whereby the electrical conductance (EC) of 1:99 sediment-water mixtures is measured after the sample has been agitated a suitable amount of time. Slow dissolution of suspended sediment in ephemeral streamflow may cause the salinity of the flow to be low which may not reflect the potential for further dissolution of particles carried as suspended sediment.

The Mancos Shale is composed of three landform types: badlands, pediments, and alluvial valley floors. Pediments and pediment remnants are relatively stable landforms. Channel incision of alluvial valley floors can produce large quantities of sediment, however, salt contribution will be lower because alluvium has been leached and it has a lower SMC than in-situ Mancos Shale. Badland erosion produces large amounts of sediment and, therefore, large amounts of salt either in solution or in undissolved particles of suspended sediment. Sediment and salt yield from badlands can be highly variable due to sediment storage and flushing effects, but overall erosion is rapid and runoff salinity is high.

Experimental erosion studies on Mancos hillslopes reveal a positive relationship between salt production and sediment yield as well as a positive relationship between slope angle and sediment and salt production. Long-term studies of Mancos Shale watersheds show that seasonal changes in the soil surface have a significant effect on infiltration capacity, runoff, and sediment yield. Disturbance of the fragile surface in the spring by animals or off-road vehicles will cause a significant increase in sediment and, therefore, salt yield.

Geomorphic studies of Mancos Shale terrain in the Upper Colorado River Basin will provide an understanding of the process of salt contribution from diffuse sources in the Upper Basin. Identification of landforms, processes, and stages of landform development will reveal the areas and mechanisms contributing sediment and salt to the Colorado River.

1) INTRODUCTION

More than 14.5 million people and 2.5 million acres of agricultural land require water from the Colorado River (Kircher, 1984). The variety of demands on this water places great emphasis not only on the quantity of water, but also on its quality. The situation is complicated nationally because seven states are involved: Wyoming, Colorado, Utah, New Mexico, Arizona, Nevada, and California (Mann et al, 1974), and it is further complicated internationally by Mexico's use of this water and the international agreement concerning Colorado River water (Holburt, 1977).

Salinity of the Colorado River

As the river flows from its source in the Rocky Mountains the dissolved solid concentration increases from about 50 mg/l to about 850 mg/l at Imperial Dam. In 1983 the cost of this increase of salinity was about 91 million dollars. Jonez (1984) indicates that the source of the dissolved solids is as follows:

- natural sources, 47%
- irrigation, 37%
- reservoir evaporation, 12%
- water exports, 3%
- municipal and industrial use, 1%

Blackman et al (1973) estimate that 84% of the natural sources of salinity within the Upper Colorado River Basin are due to diffuse sources.

The purpose of this report is to consider one aspect of the natural sources, the diffuse-source salinity in the Upper Colorado River Basin, particularly the Mancos-Shale terrain that comprises large parts of the Colorado, Gunnison, Green and Price River basins. Extensive outcrops of Mancos Shale and similar rocks occur elsewhere in the Upper Colorado River, for example, in the San Juan River basin and in many smaller tributaries to the Colorado River. In addition, based upon a review of previous research, diffuse-source salinity control measures will be evaluated and recommendations will be made for future studies.

The bulk of the field-oriented research on diffuse-source salinity has been performed by three groups: 1) the Utah State University group in the Price River drainage (the western area); 2) the U.S. Geological Survey in the badlands of Badger Wash; and 3) the Colorado State University group in the area between Grand Junction and West Salt Creek (Fig. 3.1), which includes the Badger Wash drainage basin (the eastern area).

Definitions

Natural sources of salinity are either diffuse or point sources. Saline point sources are associated with a specific site such as a spring or seep as well as saline effluents of urban, industrial and agricultural origin. Diffuse-sources in contrast (Chilingar, 1956; Gorham, 1961), and salinity results from exposure and erosion of saline rocks or soils. There should be many point sources within a diffuse-source area.

Salinity may be defined as the total quantity of inorganic soluble constituents residing within an aqueous solution. As such, it is often termed total dissolved solids (TDS). Salinity (solute concentration or SC) is customarily expressed in mg/l or ppm, or in units of specific electrical conductance most commonly at a reference temperature of 25°C. Electrical conductance (EC) has been widely used to determine salinity because solutes are primarily charged particles, and the total positive or negative charge correlates highly with salinity (SC):

$$SC = k\ EC \tag{1-1}$$

where SC and EC are given in mg/l and µmho/cm, respectively, and k is a constant ranging from 0.55 to 0.65 unless the solution has an unusual composition (Hem, 1970).

Solute load (SL) is defined as the weight of solutes discharged per unit time. It is equal to the product of SC and water discharge (Q):

$$SL = (SC)Q \tag{1-2}$$

The unit of Q is expressed as weight per time when SC is expressed in ppm, and it is expressed as volume per time when SC is expressed in mg/l. A related parameter, solute yield (SY), refers to the solute load per unit source area (A). It is equal to

$$SY = SL/A = (SC)Q/A \quad (1\text{-}3)$$

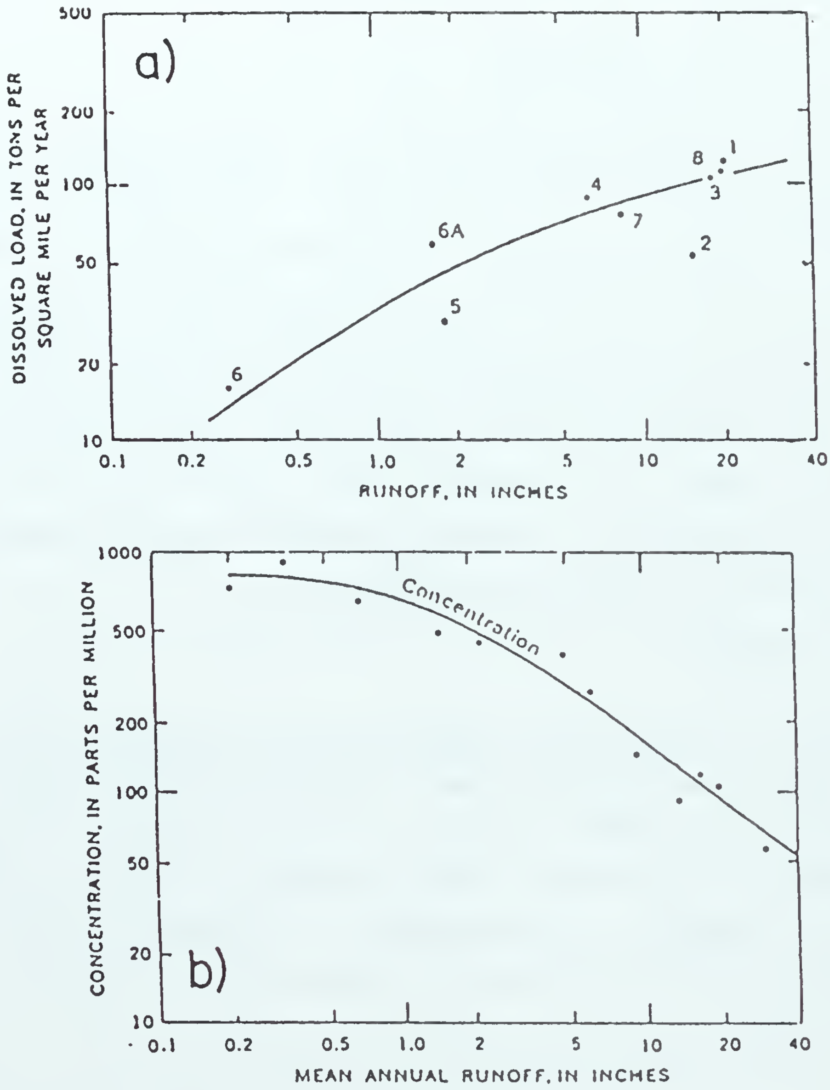
Saline water contains a high SC. The classification of water according to SC (fresh: 0-1000 ppm; salty: 10,000-100,000 ppm; and brine: > 100,000 ppm) will not be used because salinity is relative. For instance, an SC of 500 mg/l is the recommended drinking water standard limit set by the U.S. Public Health Service (1962). The recommended SC limit for industrial use varies with each industry (e.g. 500 mg/l for distilling and brewing light drinks < 3000 mg/l for boiler feed; 300-500 mg/l for paper pulp; and 100 mg/l for confectionary--(Todd, 1970)). Moreover, irrigation water may be more or less saline depending on the crops being grown.

Cause of High Salinity

Craig (1970) contends that high salinity is the result of five conditions and processes as follows: 1) water is initially saline (i.e., juvenile hydrothermal fluids; 2) "salt sieving" or membrane effects, primarily in oil field brines; 3) solution from sediment and host rocks; 4) evaporative concentration of seawater and saline lake water; and 5) artificial contamination from municipal, industrial, or agricultural waste.

Climate is the single most important environmental factor affecting the occurrence of high solute concentrations in surface water that is derived from diffuse sources, but geology, topography and biota can also be important (Peters, 1984). Geology is especially important in Mancos-Shale terrain.

All water contains dissolved solids, but only under certain circumstances does this become a serious problem. In fact, because of aggressive weathering the solute load is higher in humid regions (Fig. 1-1a), where the large discharge produces a high total dissolved load (Peters, 1984). Nevertheless, it is in the drier regions that salinity problems are greatest because concentrations are high (Fig. 1-1b). Arid



1-1 Effect of annual runoff on dissolved load (a) and concentration (b) in surface waters.

Numbers indicate major river basins in the United States. 1, North Atlantic Slope Basins. 2, South Atlantic Slope Basins. 3, Eastern Gulf of Mexico Basins. 4, Mississippi River Basin. 5, Western Gulf of Mexico Basins. 6, Colorado River Basin above Yuma, Arizona. 6A, Colorado River Basin above Grand Canyon. 7, Pacific Slope Basins in California, and 8, Columbia River and North Pacific Slope Basins (from Langbein and Dawdy, 1964).

and semiarid regions are by definition areas of low annual precipitation and high potential evaporation, and the natural waters of these regions become more concentrated. Therefore, saline accumulations appear on the surface and in the soils of drylands. The saline deposits are composed of slightly soluble minerals (most carbonates), more soluble sulfates of calcium, sodium, and magnesium, and highly soluble minerals--the nitrates and chlorides.

Runoff encountering these soluble saline accumulations acquires a high salinity (Chebotarev, 1955; Casey, 1972). This process is particularly noteworthy when the underlying bedrock contains a high soluble mineral content (SMC) and it is eroded. A high SMC characterizes fine-grained, typically shaly marine formations, such as the Mancos Shale (Fisher et al, 1961).

Topography also affects the occurrence of saline surface water (Holmes, 1971). Steep highly erodible hillslopes that contain a high SMC in conjunction with high intensity, erosive storm events may produce highly saline runoff.

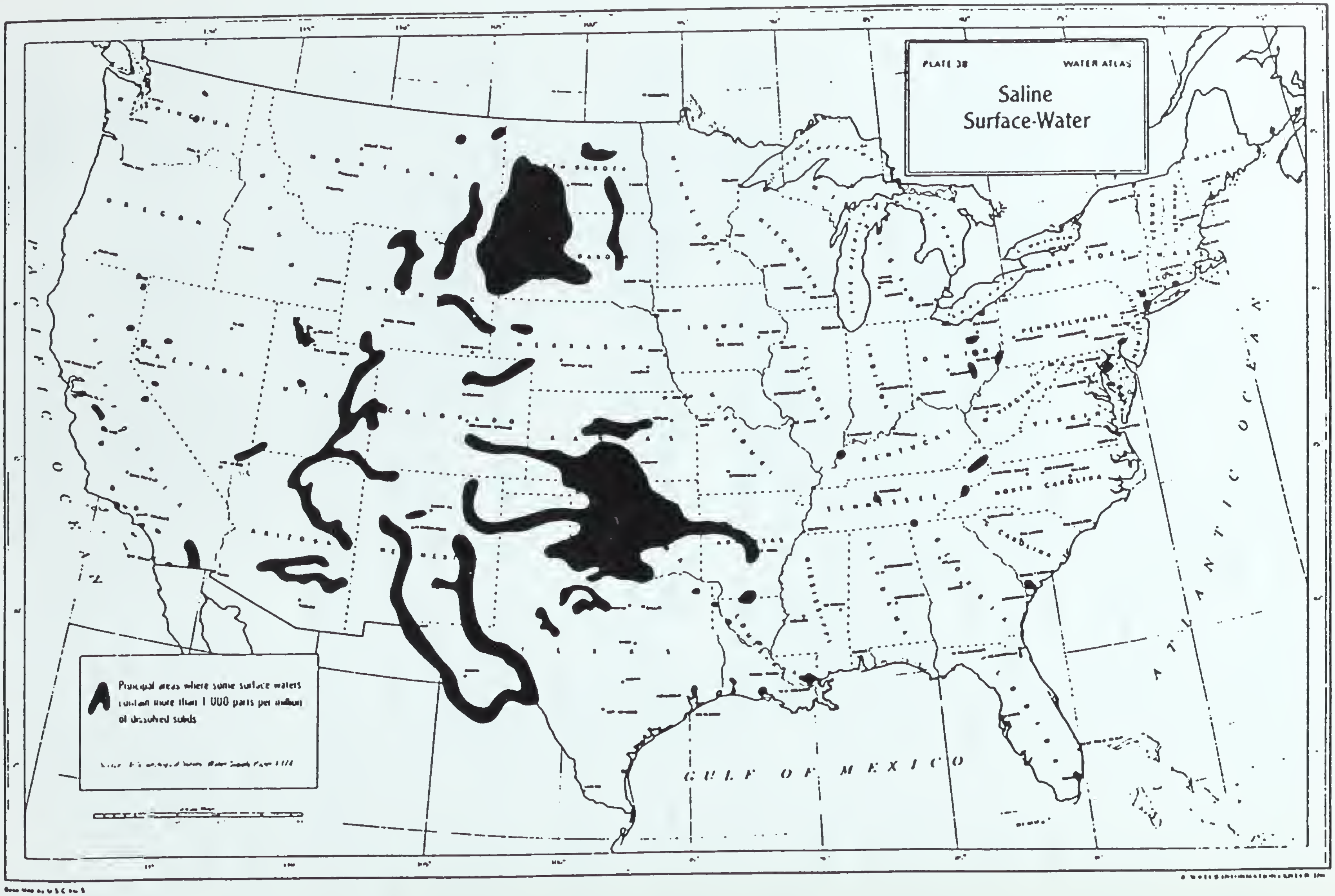
In summary, aridity, steep topography, and the presence of erodible saline surficial materials, will produce highly saline surface waters.

Distribution of Salinity

Arid to semiarid climates are closely associated with the occurrence of salinity. Figure 1-2 shows areas of the USA where surface water contains more than 1000 mg/l of solutes. Large parts of the semiarid Midwest and arid Southwest, are characterized by saline surface water, that is associated with saline soils. The saline surficial materials of these regions are the source of the salinity in the waters that drain from them.

Although considerable salt loading occurs in the Rio Grande and in the Arkansas and Missouri Rivers, much of the downstream increase in salinity in these basins is associated with irrigation and/or with saline groundwater flow, the later being the principle source of salinity in the northern Midwest.

The problem is aggravated in the Colorado River basin because the river flows from high to low precipitation areas in contrast to the



1-2 Distribution of saline (>1000 ppm) surface waters within the conterminous United States (after Geraghty et al, 1973).

Missouri, Platte, Arkansas, Canadian and Rio Grande Rivers which all flow into more humid regions. The increased discharge, of course, dilutes and decreases the salinity of these rivers.

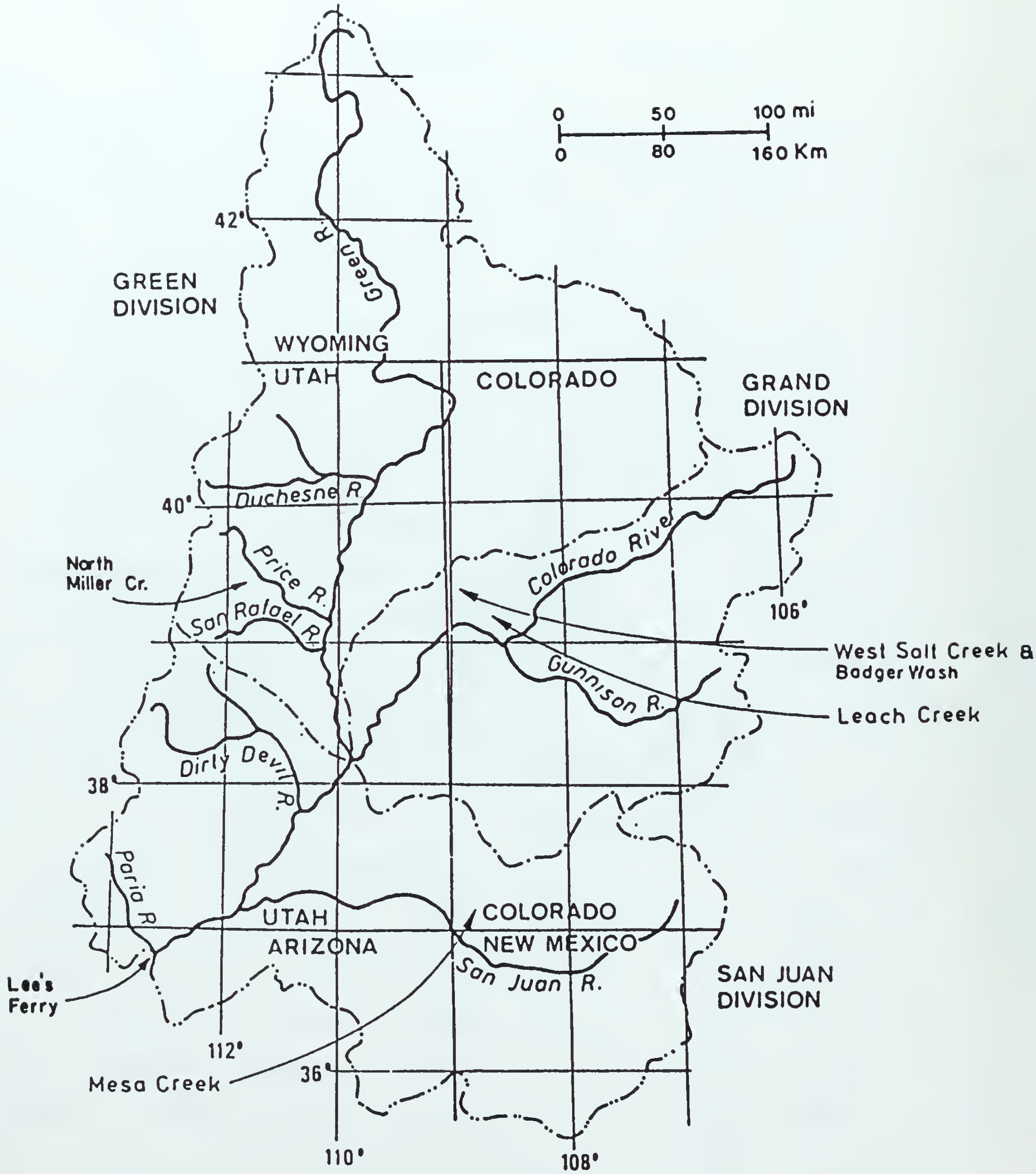
The Upper Colorado River Basin

Much of the research on diffuse-source salinity has been done in the Upper Colorado River Basin, which is defined as the area (276,000 km^2) drained by the Colorado River above Lee's Ferry, Arizona (Fig. 1-3). Most of the water in the Upper Colorado River Basin originates from spring snow melt in the high country of the Rocky Mountains. At the high elevations outcrops of Precambrian crystalline rocks produce relatively insoluble weathering products, which are characterized by low solute and sediment production. However, at the lower elevations the upper Colorado River Basin is underlain by Paleozoic to Recent sedimentary rocks, including thick marine shales. Water derived from such outcrops in semiarid areas has a high salt content.

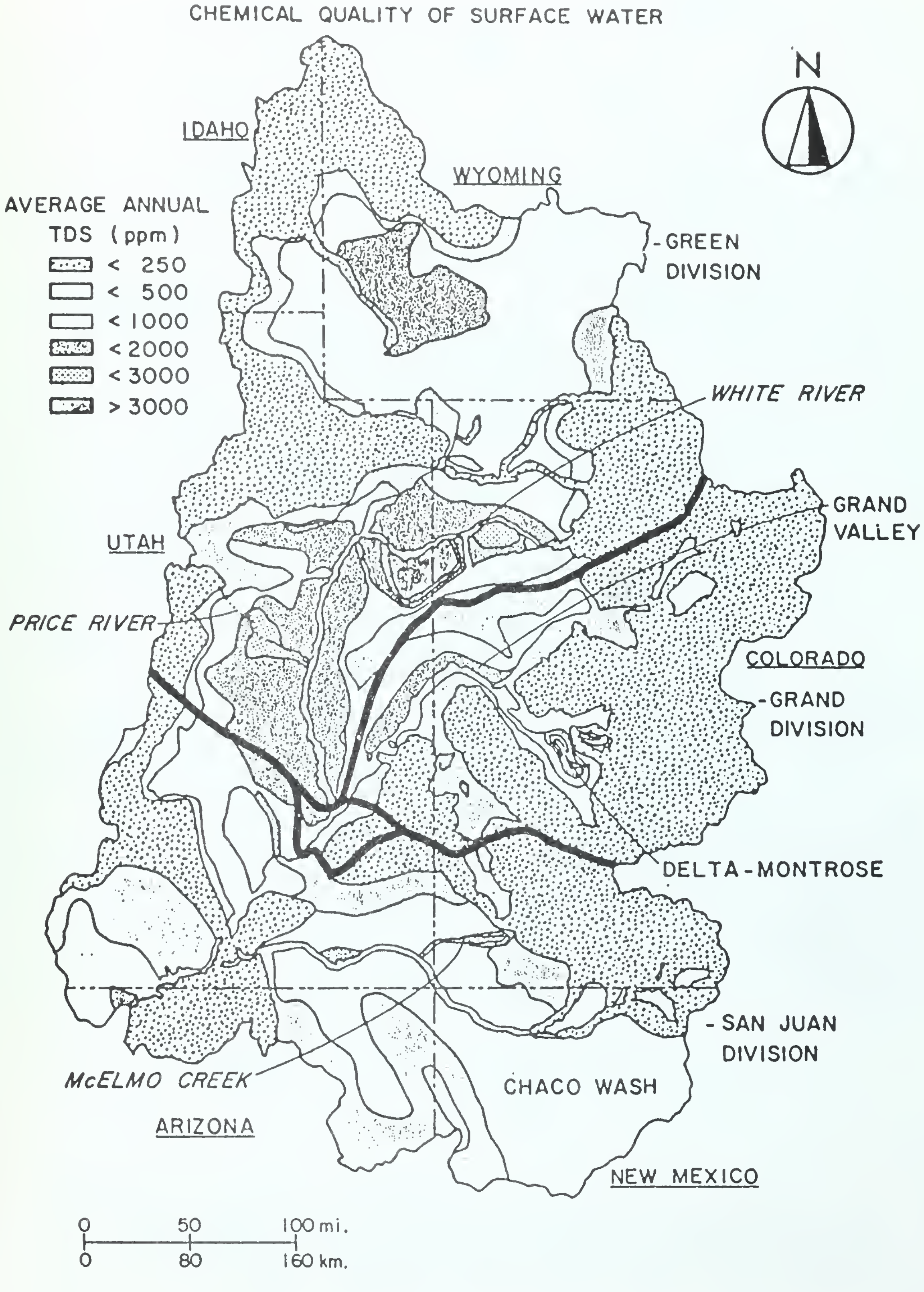
The quality of surface water in the Upper Colorado River Basin varies considerably (Fig. 1-4). The high elevations yield high quality runoff, whereas the lowlands yield more saline runoff. Solute and sediment concentrations in the mountains are approximately one order of magnitude lower than at the lower elevations (Fig. 1-5). Saline springs occur in several parts of the basin, particularly at mountain fronts and in association with salt structures (e.g. within Paradox Valley).

The major point sources (such as the Dotsero-Glenwood Springs) have been identified in the Upper Basin (e.g. U.S. Bureau of Reclamation, 1976). In addition, saline groundwater movement, recharge, and yields have been documented (e.g. Schneider, 1975; Warner and Heimes, 1979). In contrast, shallow, subsurface movement or interflow contributions to salinity have not been studied in detail. However, McWhorter and Skogerboe (1979) maintain that this contribution is minimal and that saline interflow occurs only under restricted conditions.

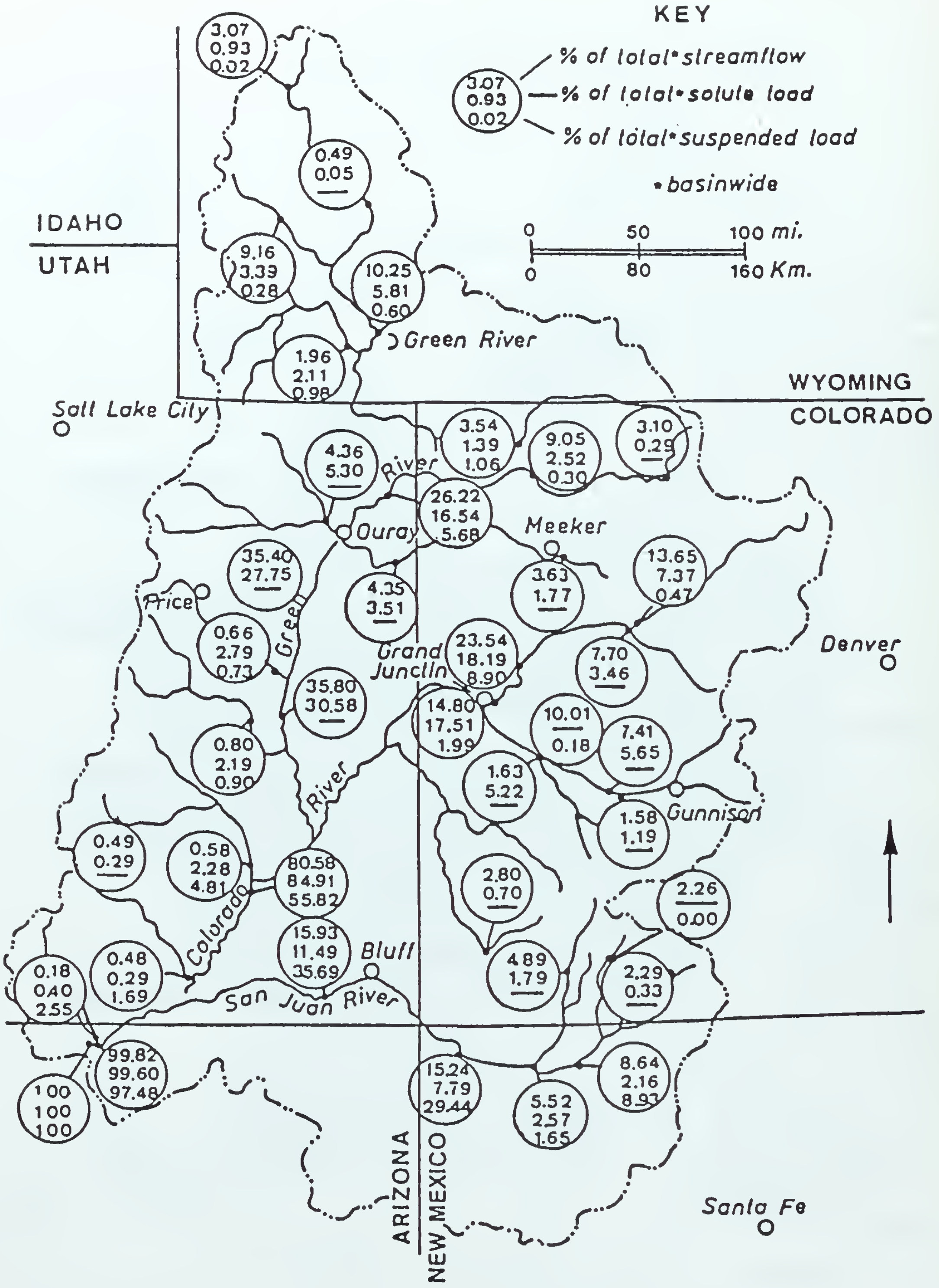
More has been written on salinity due to irrigation (Evans, Walker, and Skogerboe, 1981) than on any other single water quality topic because as much as one-third of the solute load of the Colorado River, approximately a million ton/yr at Imperial Dam, California, is attributed to irrigation (Strand, Boesch, and Kruse, 1981).



1-3 Map of the Upper Colorado River Basin showing the location of some study areas (after Shen et al, 1981).



1-4 Quality of surface water in the Upper Colorado River Basin (after Reir and Wadell, 1973).



1-5 Mean long-term solute, sediment and water discharges, expressed as percentages of the combined solute, sediment and water discharges of the Colorado and Paria Rivers at Lees Ferry, Arizona (after Iorns, Hembree and Oakland, 1965).

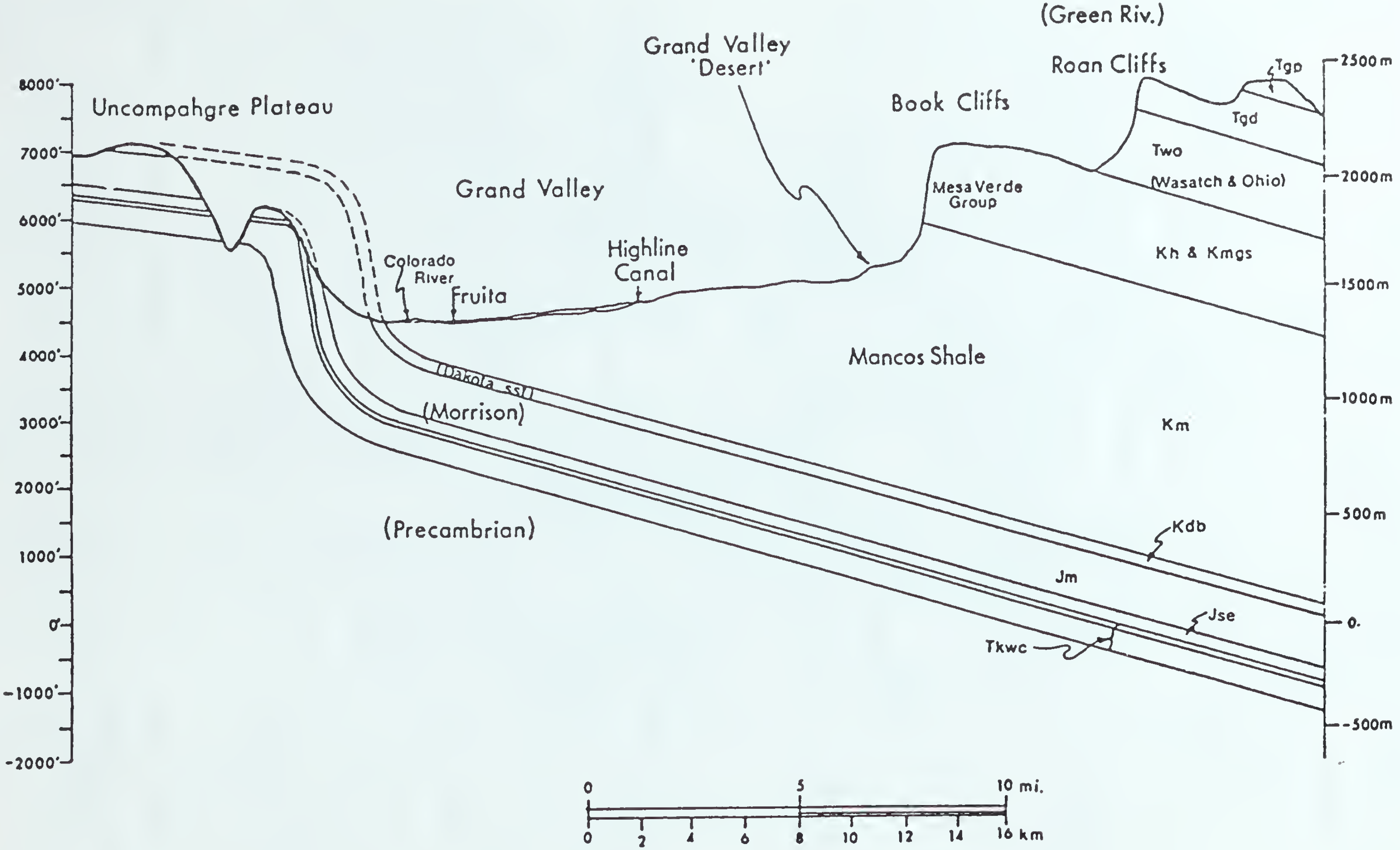
Between 1965 and 1983 decreasing dissolved-solids concentrations were detected at 20 stations on the Colorado River and tributaries (Kircher, 1984). Increasing concentrations were detected in three tributary streams (Dolores R. near Cisco, Utah; Little Snake R. near Lily, Co.; Virgin R. at Littlefield AZ). Three stations showed no change. The decreased concentration can be due to several factors; for example this period was one of major reservoir filling, improved irrigation practices and, attempts to control point-source salinity. In addition, beginning in about 1940 and continuing to about 1980 there was a substantial reduction of grazing pressure on the Public Lands, which was accompanied by a marked improvement of range conditions (U.S. Bureau of Land Management, 1985). In order to understand the salinity problem in the Upper Colorado River Basin short and long term salinity variations must be understood, and this will involve a geomorphic overview of the basins with special attention being paid to channel changes with time.

Geology

The Colorado River Basin drains all or parts of five physiographic provinces: Middle and Southern Rocky Mountains, Wyoming Basin, Colorado Plateau, and Basin and Range Provinces.

Highly erodible shales are exposed throughout the Upper Colorado River Basin lowlands. Because of its thickness, usually over 600 m and at times over 1000 m, the outcrop area of Mancos Shale is the largest among the sedimentary rocks (Figure 1-6). Mancos Shale has been studied more than any other formation in connection with salinity because of its large exposures, its erodibility, and its high SMC. The name Mancos was first applied in 1899 by Cross (Fisher, Erdmann, and Reeside, 1961) to exposures of shale near the town of Mancos in southwestern Colorado.

The Mancos Shale is a shallow-water marine formation. It is thinly bedded and dark gray, when fresh. The shale contains numerous veinlets of gypsum and calcite, and when weathered it is a lighter gray. The surface is a friable, semi-powdery mass when dry that becomes sticky and impervious when wet. It includes a few thin layers of bentonite, calcareous sandstone, and shaly limestone. In places it includes



1-6 Geologic cross section of the Grand Valley (after Schneider, 1975). The vertical exaggeration is 8x. Formation names are given in parentheses.

lenticular carbonaceous and coal-bearing shale and sandstone. The soluble minerals contained within Mancos Shale, primarily sulfates of calcium, magnesium, and sodium, comprise an average of two percent by weight of weathered surficial shale.

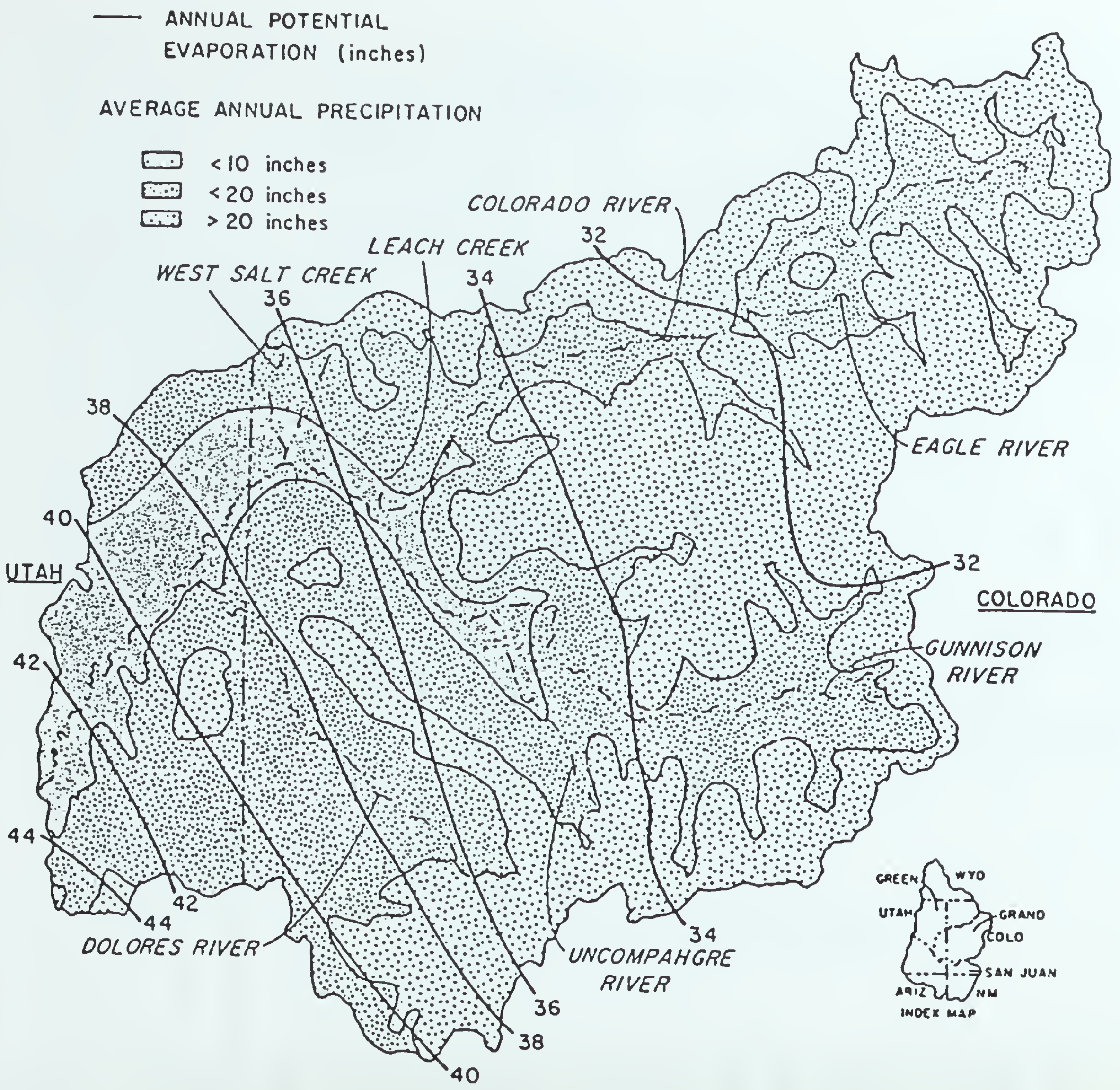
Climate, Vegetation, and Soils

The climate in the lowlands of the Upper Colorado River Basin is of a semiarid continental type with frequent high intensity convective storms of small areal coverage (Fig. 1-7). Maximum monthly precipitation occurs in July-August. In the Book Cliffs desert, daily and seasonal temperatures vary widely with extremes of 42 to -41° C (Mundorff, 1972). The average potential evaporation measured with a class-A pan at the Grand Junction airport is 233 cm with a monthly average of 46.5 cm in July (Lusby, Reid, and Knipe, 1971). Mean annual precipitation is 250 mm at Price, 200 mm at Woodside in the lower Price Basin, and 215 mm at Badger Wash near Grand Junction (Branson and Owen, 1970; Mundorff, 1972).

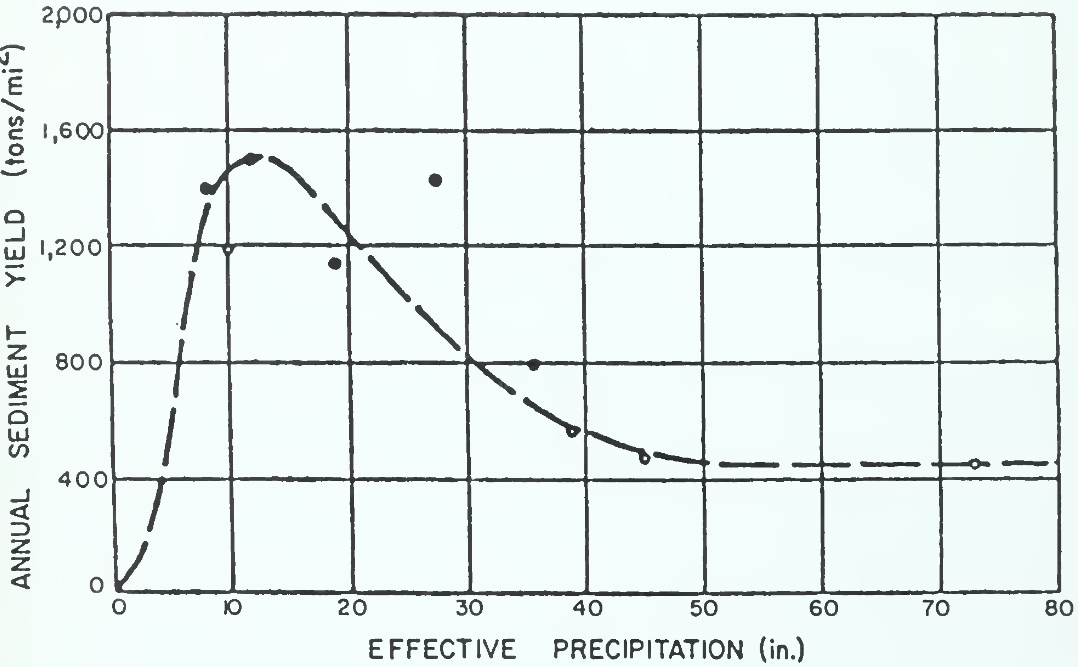
The crowns of living perennial plants cover less than 10 percent of the surface except locally and there is less than 1 percent vegetational cover on the steeper hillsides. Greasewood and rabbitbrush grow on alluvial fills in the valley bottoms. Sagebrush is found on the gravel-covered pediments below pinon-juniper stands on higher ground. Mat saltbrush and shadscale dominate the barren Mancos Shale terrain.

Knobel et al (1955), Swenson et al (1970), Lusby et al (1971), and Schafer (1981) have investigated and classified the soils derived from and developed on Mancos Shale. These thin gray shale soils have a pH of 8.0, a bulk density of 1.31-1.35 g/cm^3 in the A_1 horizon, and a high salinity. They contain montmorillonite, illite, chlorite, and mica. Both fresh and somewhat weathered Mancos Shale swells considerably when wetted with a 25-50 percent volume increase in free swell tests (Schumm, 1964).

Data from small drainage basins on the Mancos Shale (Badger Wash) were used by Langbein and Schumm (1958) to prove that semiarid regions are those that produce the largest sediment yields per unit area (Fig. 1-8). The curve demonstrates that Mancos Shale terrain in western



1-7 Mean annual precipitation and potential evaporation in the Grand River Basin (after Iorns, Hembree, and Oakland, 1965).



1-8 Effect of precipitation on sediment yield as determined from reservoir surveys (from Langbein and Schumm, 1958).

Colorado and in Utah, is highly erodible and that large quantities of sediment are produced by small Mancos-Shale drainage basins. The ratio of salt to sediment produced from three of the Badger Wash drainage basins is 3.8% (Jackson et al, 1984).

2) DIFFUSE-SOURCE SALINITY

Diffuse-source salinity is significantly influenced by the soluble-mineral content (SMC) of soils and rocks exposed at the earth's surface (Peters, 1984), and runoff salinity increases with the SMC of these surface materials.

Origin of Soluble Minerals

The amount and type of minerals present in rocks and soils is a function of storage, leaching and accumulation processes. Some minerals are formed in situ. For instance, marine deposits contain connate water almost identical to seawater. Therefore, prior to appreciable leaching or accumulation, marine shales and sandstones have a high SMC (Garrels and Thompson, 1962). Unlike marine sediments, freshwater sediments, and igneous and metamorphic rocks rarely have a high SMC. Chlorides, bicarbonates sulfates, and nitrates generally comprise less than 0.1% of unaltered igneous rocks.

Almost all rocks undergo secondary mineralization, and soils, by definition, undergo pedogenic processes that lead to preferential leaching and/or accumulation. In situ accumulation may occur, but the primary accumulation of soluble minerals is rarely by in-place weathering. Cyclicsalts in the form of dry fallout and rainout may contribute large amounts of soluble minerals to the surface. Fallout, which includes wind-blown sand and dust that is derived from saline materials may concentrate soluble minerals. Rainfall and precipitation in general have a very low salinity (Carroll, 1962), and, therefore, they are not the direct cause of the accumulation of soluble minerals.

Transpiration of plants and the loss of minerals and nutrients from plant leaves by the leaching action of rainfall, mist and dew has been assumed to contribute large quantities of leachates from living plants and litter. However, a recent study of Malekuti and Gifford (1978) in the Upper Colorado River Basin has shown that plants contribute merely 0.01-0.02 percent or less of the total annual salt load of the Price River Basin. Certain species of saltbush, shadscale, greasewood, salt cedar and halogeton provided the highest concentrations of leachate, which can be as high as 721.1 mg/l from 50 g of greasewood litter that had been leached by 76 mm of simulated rainfall that was applied during one hour. Nevertheless, on the alluvial valley floors of the Colorado Plateau, water use by phreatophytes concentrates salts in the subsurface (U.S. Bureau of Land Management, 1984, Table 7), and SC concentrations of 5,800 to 11,000 mg/l were measured in shallow groundwater beneath salt cedar (Tamari pentandra)(Woessner et al, 1984). In fact, in the lower Virgin River about one-third of the water is used, and one-third of the salts are stored by phreatophytes.

By far, the most common method of soluble mineral accumulation is evaporation of soil water. Evaporation from the soil surface continues as water is replenished by upward capillary movement (Laronne, 1977). In fact, the "critical" groundwater level, the depth at which evaporation rate decreases only slightly with further increase of water table depth, is about 150-200 cm for fine sandy loams, but it is as much as 1500 cm for coarse sandy soils. Salt concentration gradients (and thermal gradients causing diffusion in soil water) are known to increase the upward flow of soil water, although buildup of salt crust may reduce evaporation (Qayyum, 1961).

Anthropogenic activity leading to accumulation of soluble minerals is very common in irrigated semiarid lands. Man-induced salinization is caused by raising the water table by over-irrigation and improper irrigation scheduling, poor drainage, and canal seepage. Other activities leading to salinization are the use of saline water for irrigation, under irrigation, and poorly levelled land which prevents leaching (U.S.D.A., 1954; Ayers and Westcot, 1976; Evans, Walker and Skogerboe, 1981). Nevertheless, it is the high soluble mineral content of the Mancos Shale and similar formations that is the main source of Colorado River salts.

Mineralogy of Soluble Minerals

Samples of Mancos Shale, shales of the Lower Mesa Verde Group, and associated surficial alluvium from the Grand Valley in Colorado and in the vicinity of the confluence of the Price and Green Rivers, Utah have been analyzed by Whittig (written comm., 1979) using X-ray diffraction techniques in order to determine the mineralized composition of the soluble materials. Calcite, dolomite, gypsum, and other more soluble carbonates and sulfates were detected (Table 2-1). All samples of alluvium were composed primarily of quartz and feldspars, and shale samples additionally contained appreciable quantities of clay minerals - montmorillonite, illite, chlorite, and mica. Highly soluble evaporites such as the chlorides and nitrates were not present in detectable amounts, with one exception. Gypsum ($CaSO_4$ $2H_2O$) comprised the bulk of the moderately soluble minerals in most instances, with smaller quantities of hydrated Na and Mg sulfates.

The mineralogic character of the sampled alluvium and shales indicates that the highly soluble fraction of these surficial materials has been leached. In fact, the most soluble evaporites would have remained in situ only under extremely arid conditions.

X-ray diffraction maxima of samples collected from a Mancos Shale hillslope in Indian Wash indicate the prevalence of gypsum on the surface and in underlying material, primarily as large (> 2mm) crystals Although the average size of gypsum crystals is smaller in channel bed materials than on the hillslopes a considerable quantity of granule-sized soluble mineral is still present in the bed of first order channels, although most gypsum crystals dissolve further downstream (Shen et al, 1981).

The predominance of gypsum, Na-Mg sulfates and carbonates indicates that their dissolution will yield a relatively saline water of the Ca (Na, Mg) - SO_4 (HCO_3) type. Indeed, hydrologic investigations of Colorado River water extending from the mountains downstream to the mouth of the Colorado River have shown that these are the primary inorganic soluble constituents (Iorns, Hembree and Oakland, 1965; Mundorff, 1972; U.S.Bureau of Reclamation, 1974; Shen et al, 1981).

Solubility

One aspect of chemical kinetics, which is the study of solute release rate, is relevant to an understanding of diffuse-source salinity. The rate of release may determine which process is responsible for the bulk of solute yields. For instance, a slow dissolution rate may imply that only subsurface flow that is in contact with soil and rocks for a long time is responsible for most of the solute yield. Overland flow, usually short-lived, may be a dominant solute producing mechanism if the dissolution rate is high.

Table 2-1. Minerals detected by X-ray diffraction in samples from the Upper Colorado River Basin. Numbers represent mineral concentrations on a relative scale from 1 to 10 (from Shen et al, 1981).

			mineral												
	Sample	Particle size (mm)	$CaCO_3$	$CaMg(CO_3)_2$	$NaHCO_3$	$Na_2CO_3 \cdot 10H_2O$	$Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$	$CaSO_4 \cdot 1/2H_2O$	$CaSO_4 \cdot 2H_2O$	Na_2SO_4	$Na_2SO_4 \cdot 10H_2O$	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	$MgSO_4 \cdot 6H_2O$	$MgSO_4 \cdot 7H_2O$	$NaCl$
<u>West Salt Creek</u>															
Bed Crust	156		2	1					0.5	1		1	T		
Bank crust	158		1.5	5.5								0.5			
Soil under bank crust	159		0.5	1.5					0.5						
Mancos shale, weathered talus	169		10+	7					T						
Soil, from Mancos Shale	173		1	4					10+	T		T			
Bed of channel	G7A1S	>1	1	3					0.5	T		T			
Bed of channel	G7A2S	<1	3	3.5					0.5	T		0.5			
Efflorescence, channel bed	G8B1	>1	1	3					T	1		5	0.5		
Efflorescence, channel bed	G8B1	<1	1	1.5					T	0.5		2.5	1		
Salt seep (air dry)	G8			T						10+	0.5	10+		T	
Salt seep (field moist)	G8			1		0.5				3	10+			3	
Salt from creek bed	X2		T	1			T	T	0.5	3.5	0.5	10+	1	0.5	T
<u>South Canyon, West Salt Creek</u>															
Bank crust, Mesa Verde Fm.	162		0.5	4.5					T				T		
<u>Prairie Canyon, West Salt Creek</u>															
Bed crust	175		2	2.5		0.5			T	T					
Bed crust	176		2	2											
<u>Badger Wash</u>															
Soil Mancos Shale surface	X6		1.5	7		T	T	T	T	0.5			1	T	
<u>Leach Creek</u>															
Efflorescence, Mancos Shale	X3		T	1					1						
Weathered Mancos Shale	X5		T	2	0.5		T		2.5		T		T		
Bed Crust (0-2 cm), alluvium	G1B1	>1	2	3.5					1						
Bed crust (0-2 cm), alluvium	G1B1	<1	2	4.5					0.5						
Mancos Shale, hillslope	G1E3	>1	2.5	7.5					5						
Mancos Shale, hillslope	G1E3	<1	2	7.5					5						
Bed of channel, alluvium	G2A1	>1	2.5	8					6	T					
Bed of channel, alluvium	G2A1	<1	3.5	7					7.5					1	
Crust, Mesa Verde shale	G20A	>1	T	3					6						
Crust, Mesa Verde shale	G20A	<1		1.5					0.5						
<u>Green River</u>															
Weathered Mancos Shale	164		5	4				1	T	0.5				T	T
Unweathered Mancos Shale	165		5	5					T	T					
Fresh Mancos Shale	X1		3.5	4.5		T		T	T					T	T
Sandy shale, bedrock	167		3.5	7											
Exposed salt layer	168		10+	3					10+						
Evaporite Mancos Shale	X4								10+						
<u>North Miller Creek</u>															
Channel bed efflorescence	USC4A	>1	5.5	5.5					0.5	T				1	
Channel bed efflorescence	USC4A	<1	4	6					1	T			T		
Channel bed efflorescence	USM2A	>1	3.5	8.5		T	T	T						T	1
Channel bed efflorescence	USM2A	<1	2	2					T	T			0.5		
Mancos Shale mass wasted	USIJ	>1	4.5	8					2.5	T			T		
Mancos Shale mass wasted	USIJ	<1	2.5	3					1.5	0.5			0.5		
Channel bed Mancos Shale crust	U6F1	>1	3	3.5					0.5				T		
Channel bed Mancos Shale Crust	U6F1	<1	3	4.5					1	0.5			T		

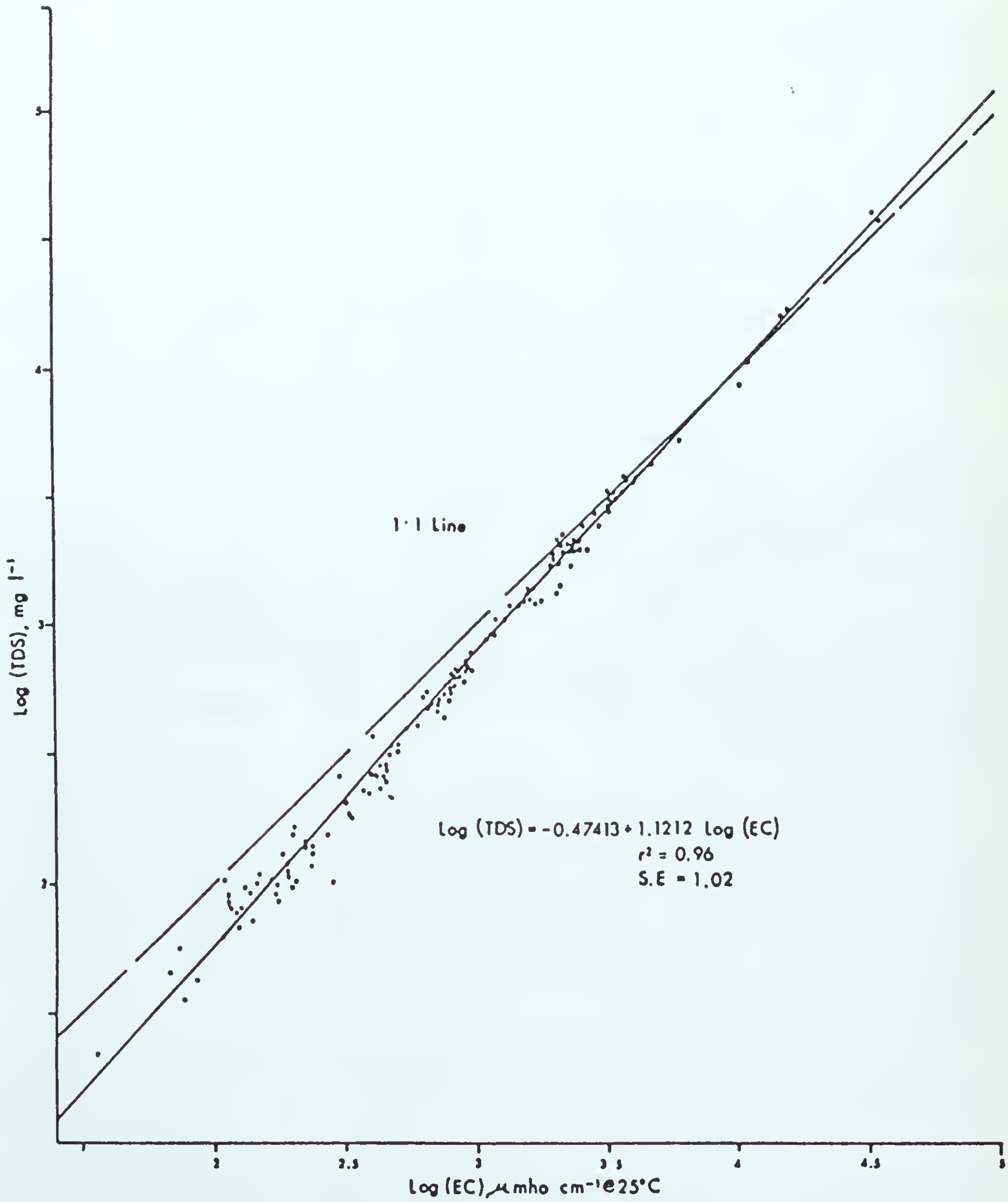
Agronomists and agricultural engineers use filtered saturated paste extracts of 1:1 soil-water-ratio extracts to determine the soluble mineral content (SMC) of soils (U.S. Dept. Agr., 1954). These determinations are based on a shaking time of one hour or, at times, of 24 hours. The effects of contact time and sediment-water ratios on rate and extent of dissolution are not taken into consideration in this technique of determining SMC. Therefore, a different procedure was developed by Laronne (1977). In order to simulate the dissolution of transported sediment, he calculated SMC from the quantity of solutes released from 1:99 sediment/water mixtures.

The calculation of SMC usually requires determination of the concentration of solutes (SC) of the aqueous solution either by undertaking a complete chemical analysis or by the evaporation method. Because both techniques are time consuming and expensive,electrical conductance (EC) has been used as an index of SC by numerous researchers (Hem, 1970; Lane, 1975). Laronne (1977) derived an empirical relationship between SC and EC of sediment-water mixtures of Mancos Shale and associated alluvium (Fig. 2-1). Shen et al (1981) developed another relationship

$$SC = 5.3 \cdot 10^{-6} EC^2 + 1.05 EC - 348.4 \qquad (2\text{-}2)$$

where SC is expressed in mg/l and EC in µmho/cm at 25°C. The equations estimate SC equally well and both are non-linear. Linear equations ($SC = kEC$, k is a constant) are customarily used for low solute concentrations (Hem, 1970).

Laronne (1981) sampled alluvium, primarily comprised of sandstone and sandstone-derived particles from the Mesa Verde Formation, that was in proximity to Mancos Shale, from the bed, gully walls and banks of West Salt Creek. Sediment samples were placed in 500 ml Erlenmeyer flasks to which predetermined quantities of distilled water (EC in the range 1.5 - 8 µmho/cm and $5.5 < pH < 6.5$) were added. The samples were shaken for various periods of time. Initiation of these kinetic runs (time 0) began immediately upon contact of sediment and water. A similar procedure was used by Jurinak, Whitmore, and Wagenet (1977) to study the kinetics of salt release from Mancos Shale sampled in the Price River Basin. Dissoluton rates were derived from EC data.



2-1 The relation between salinity (TDS in mg/l) and electrical conductance (EC) (after Laronne, 1977).

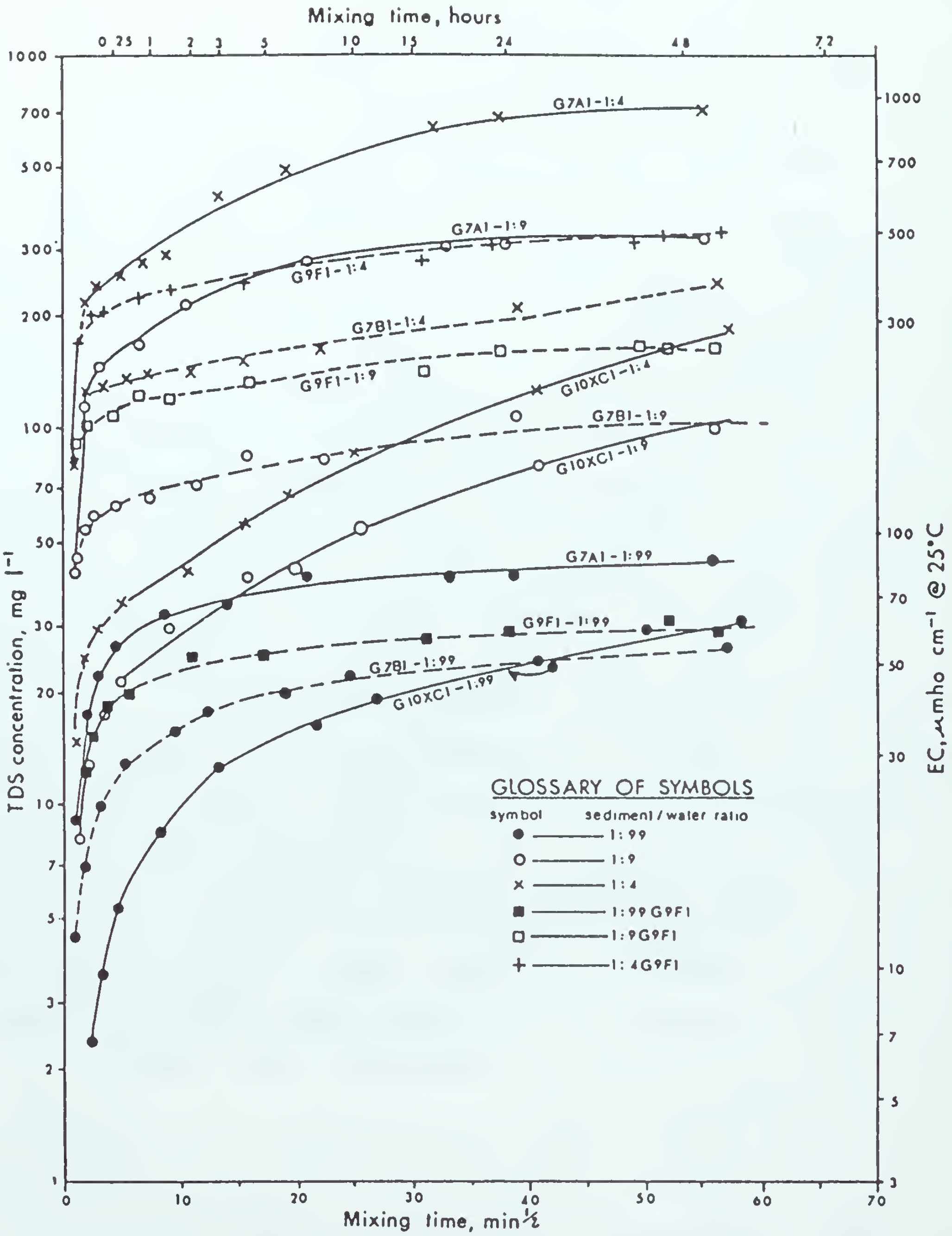
The time required to obtain accurate measurements of SMC depends on the sediment-water ratios used in the analysis. Fig. 2-2 shows that release rates of soluble minerals from samples of Mancos Shale and associated alluvium (Laronne, 1981) are variable and that many hours may be required before all soluble compounds are released from a sample. Rates of dissolution were initially very rapid, but they slowed with time. Nevertheless, some samples continued to produce dissolved solids after 48 hours. The larger the water to sediment ratio the more soluble material is released (Nezafati et al, 1981). Whitmore (1976) found a similar relation, and in addition, he showed that solutes are released more rapidly from fine-grained sediments (Fig. 2-3) (Table 2-2).

A long contact time between water and sediment is needed to approach an equilibrium SC. This indicates that in the field "runoff is unequilibrated with respect to the major soluble minerals -- during the first one or as much as a few hours of contact. Hence salinity yields derived from in situ conductance readings of runoff -- may be inadvertently but significantly underestimated (Shen et al, 1981). Also dissolution from sediment in transport should be a major source of solutes when sediment concentrations are high" (Laronne, 1981, p. 551).

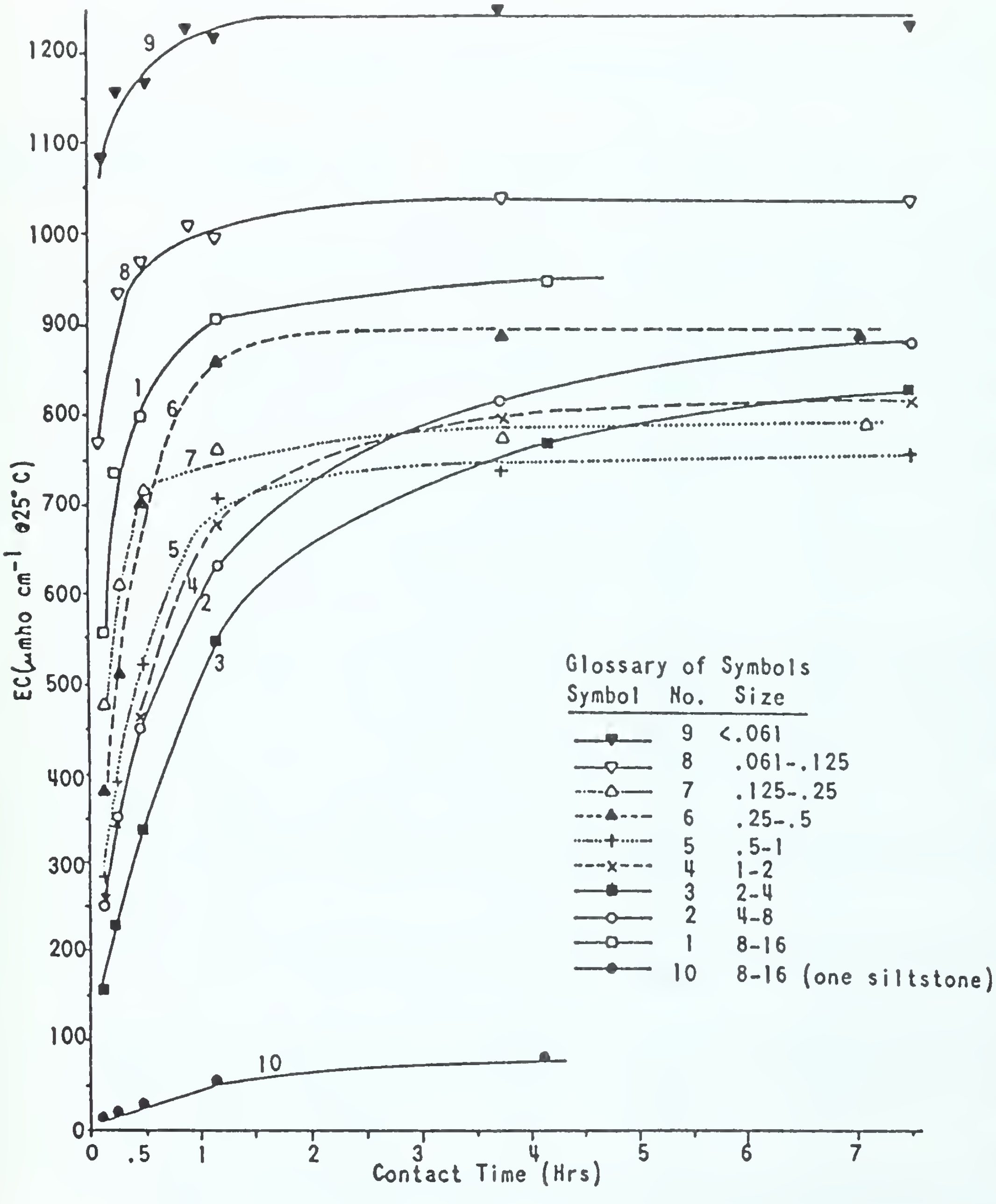
The previous description of the effect of sediment-water ratios on EC may be summarized as follows. Increased sediment concentration is the source of more soluble minerals, which, in turn, increases the salinity (SC) and, the EC of the aqueous solution. It is apparent that not all potentially soluble matter dissolves under conditions of partial equilibrium. The amount of this undissolved matter decreases as the sediment concentration decreases.

Laronne (1977) used 1:1, 1:9, 1:99, and some 1:4 and 1:999 sediment-water ratios for samples of surficial shale and alluvium to obtain data on the effect of sediment concentration on EC. The specific ion concentrations consistently increased with an increase of sediment-water ratio (Table 2-3). This is, of course, expected for unsaturated solutions to which soluble minerals are added.

When the EC of a shaken sediment-water mixture does not increase appreciably with time, it is concluded that equilibrium is approached. A series of experiments were undertaken by Laronne (1977) to determine the validity of referring to such solutions as equilibrated (or



2-2 Dissolution kinetics of Mancos Shale alluvium. Salinity increases with mixing time (after Laronne, 1981).



2-3 Effect of particle size on rate of salt release from West Salt Creek alluvium-sample G861. Salinity increases with decreasing sediment size (after Laronne, 1977).

Table 2.2. Dissolution Kinetics of a Mancos Shale sample at varying soil/water ratios and for different size classes (after Whitemore, 1976).

Data expressed as EC x 10^6 at 25°C

Time	Natural soil			Size fractions (1:1 dilution)			
	1:1 H_2O	1:10 H_2O	1:50 H_2O	1mm	.25 mm	.100 mm	<.100mm
1 sec	1154	825	98.3	799	1206	1810	2022
10 sec	1528	1060	182.2	1023	1428	2032	2210
20 sec	1970	1289	282.4	1130	1720	2246	2248
30 sec	2078	1289	350.8				
1 min	2098	1324	381.4	1238	1932	2279	2316
2 min	2074	1450	448.2				
3 min	2082	1818	452.4				
4 min	2059	1886	653.4				
5 min	2059	1932	653.0				
10 min	2098	1936	687.0	1798	2038	2289	2380
30 min	2122	1948	821.2	1842	2172	2300	2858
1 hr	2186	2062	846.1	1966	2220	2348	2400
4 hr	2132	2154	1208				
8 hr	2244	2178	1304	2321	2332	2398	2476
24 hr	2292	2300	1640	2400	2480	2556	2492
72 hr	2260	2431	1642	2432	2592	2548	2476
Equilibrium (7-9 days)	2272	2470	1656	2512	2602	2579	2481

Table 2.3. Summary of chemical analyses of selected solutions derived from aqueous mixtures (1:99, 1:9 and 1:1) of selected samples of surface materials in the Upper Colorado River Basin (after Laronne, 1977).

Depth	Concen-tration	Sample Number	EC (pmhos cm^{-1})	Ca	Mg	Na	K	SO_4	HCO_3	Cl	NO_3	CO_3	Calculated SC (mg/l)	SC 1:99 / SC 1:9
13.0-21.0	1:99	U5E3C	423.0	4.3	0.1	0.1	0.0	3.9	0.2	0.0	0.0	0.0	289.2	3.06
	1:9	U5E3C	1200.0	14.2	0.7	0.4	0.0	15.1	0.2	0.0	0.0	0.0	1039.7	
	1:1	U5E3C	3800.0	28.1	7.6	19.1	0.8	54.7	0.5	1.6	0.1	0.0	3846.6	
0.0-05	1:99	U5E4A	317.0	1.0	0.4	1.6	0.0	2.3	0.5	0.0	0.0	0.0	202.7	1.59
	1:9	U5E4A	2150.0	4.2	3.5	13.8	0.0	20.0	0.0	0.0	0.0	0.0	1404.6	
	1:1	U5E4A	15000.0	21.5	41.8	168.0	1.4	222.6	0.7	12.7	0.6	0.0	16077.8	
0.5-13.0	1:99	U5E4B	187.0	0.9	0.3	0.5	0.0	0.9	0.6	0.0	0.0	0.0	113.0	0.94
	1:9	U5E4B	1800.0	3.9	1.8	14.9	0.0	18.0	0.3	0.0	0.0	0.0	1325.4	
	1:1	U5E4B	3300.0	13.7	8.4	22.1	0.6	44.5	0.5	0.5	0.0	0.0	3093.8	
13.0-22.0	1:99	U5E4C	85.6	0.3	0.1	0.3	0.0	0.6	0.0	0.0	0.0	0.0	42.9	1.49
	1:9	U5E4C	450.0	1.0	0.5	3.2	0.0	3.5	0.8	0.0	0.0	0.0	316.6	
	1:1	U5E4C	1700.0	1.2	1.0	15.4	0.3	16.0	1.1	0.1	0.0	0.0	1241.1	
0.0-0.5	1:99	U6A1	6100.0	5.4	19.5	57.4	0.0	76.4	0.5	1.8	0.0	0.0	5428.8	1.48
	1:9	U6A1	35000.0	26.9	158.1	421.2	0.0	578.1	1.9	10.0	0.0	0.0	40381.5	
	1:1	U6A1	95000.0	23.5	2100.0	2700.0	23.8	4600.0	12.1	190.0	0.6	1.0	317519.6	
0.0-3.0	1:99	M2C1	77.2	0.4	0.1	0.1	0.0	0.5	0.0	0.0	0.0	0.0	35.5	1.68
	1:9	M2C1	422.0	2.8	0.7	0.2	0.0	3.4	0.0	0.0	0.0	0.0	232.5	
	1:1	M2C1	1300.0	11.0	3.6	0.2	0.4	14.8	0.8	0.0	0.1	0.0	1050.3	
30-6.0	1:99	M2C2	106.0	0.5	0.2	0.2	0.0	0.7	0.2	0.0	0.0	0.0	62.9	6.76
	1:9	M2C2	284.0	0.3	0.2	0.8	0.0	0.3	1.0	0.0	0.0	0.0	102.3	
	1:1	M2C2	1500.0	13.3	3.3	1.1	0.3	16.9	0.7	0.0	0.3	0.0	1216.7	
6.0-14.0	1:99	M2C3	35.8	0.2	0.1	0.1	0.0	0.3	0.0	0.0	0.0	0.0	21.9	3.33
	1:9	M2C3	139.0	0.6	0.2	0.2	0.0	0.6	0.4	0.0	0.0	0.0	72.3	
	1:1	M2C3	400.0	2.8	0.9	0.1	0.2	3.0	0.6	0.0	0.1	0.0	264.1	
0.0-1.0	1:99	M2D1	72.0	0.55	0.1	0.15	0.0	0.3	0.45	0.0	0.0	0.0	57.6	6.30
	1:9	M2D1	165.0	0.9	0.1	0.4	0.0	0.7	0.7	0.0	0.0	0.0	104.8	
	1:1	M2D1	400.0	4.2	0.3	0.2	0.3	3.1	1.9	0.0	0.0	0.0	368.9	
24.0-415	1:99	M2D4-5	173.0	1.2	0.1	0.1	0.0	1.0	0.45	0.0	0.0	0.0	87.8	1.42
	1:9	M2D4-5	841.0	8.9	1.0	0.2	0.0	9.8	0.7	0.0	0.0	0.0	678.0	
	1:1	M2D4-5	2400.0	26.9	6.1	0.5	0.2	31.2	1.9	0.0	0.0	0.0	2173.8	

approaching equilibrium). A 1:9 sediment-water mixture was shaken until the increase in EC was minimal; that is, equilibrium was reached. Water was then added until a 1:99 sediment-water mixture was achieved, and with each dilution additional dissolved solids were obtained from the sample.

Laronne (1977) also performed an additional experiment to demonstrate the presence of undissolved material, as sediment concentrations increased in three solutions. Equilibrated mixtures of each solution were rapidly heated to 75°C. A comparison of the heated to the unheated solutions (Table 2-4) shows that, as sediment concentrations increased, the percent of additional dissolved ion species due to heating increased. A marked increase of specific-ion concentrations and SC took place in both 1:99 and 1:9 solutions. The increase due to heating was greatest for Ca^{2+} in the 1:9 solutions and for HCO_3^{1-} in the 1:99 solutions. Because no significant difference exists between the specific ion concentrations and the SC increase was small for the 1:999 solution, it is inferred that most of the soluble minerals dissolved upon contact in this dilute solution while it was heated.

These experiments show that both 1:9 and 1:99 mixtures were partially equilibrated, but they contained undissolved minerals. Laronne (1977) suggests that this could be a result of the coating of particles with siliceous or ferric oxide during precipitation of evaporites. During the continuous concentration of the soil solution due to evaporation, the slightly soluble minerals are the first to precipitate out of the solution. Therefore, a slightly soluble mineral such as gypsum would be expected to be surrounded by a more complete and thicker coating than that deposited on the more soluble minerals such as sulfates of sodium and magnesium, which begin to precipitate later. Upon contact with water the most soluble minerals, those least coated with the slightly soluble ferric oxides, dissolve rapidly and more completely than gypsum or calcite. Moreover, if the coating is thick some of the particles of gypsum and calcite may not dissolve in the soil solution, because the solution may be saturated with respect to a ferric oxide, although it is undersaturated with respect to gypsum.

Table 2.4. Specific ionic concentrations (meq l^{-1}) of heated and unheated equilibrated solutions of sample U5D1A at 1:999, 1:99 and 1:9 sediment:water ratios (after Laronne, 1977).

Sediment/ Water Ratio	Remarks	Ca^{2+}	Mg^{2+}	Na^{1+}	K^{1+}	SO_4^{2-}	HCO_3^{1-}	EC (µmho cm^{-1} @ 25°C)	SC (mgl^{-1})	Increase due to Heating (%)
1:999	heated	0.4	0.1	0.2	0.1	0.4	0.2	60.0	49.2	8.4
1:999	not heated	0.4	0.1	0.2	<0.1	0.4	0.2	48.5	54.3	
1:99	heated	0.8	0.1	0.9	0.1	1.1	0.5	192.0	125.2	17.3
1:99	not heated	0.6	0.1	0.6	0.2	1.4	0.1	170.5	106.7	
1:9	heated	3.4	1.0	8.2	0.4	11.4	0.6	1275.0	868.6	49.8
1:9	not heated	1.3	0.5	6.6	0.2	7.6	0.4	1043.0	579.9	

Summary

Although many factors can contribute to salinity on the Mancos-Shale terrain, the major factor is the presence of soluble minerals that were precipitated as the Mancos Shale was deposited. The most important soluble mineral is gypsum.

Empirical relations between salinity (SC) and conductance (EC) have been developed that permit rapid and inexpensive determination of salinity and SMC of each material. However, care must be taken when determinations of SMC of sediment samples are made. Laronne (1977) demonstrated that in order to obtain an accurate measurement of SMC, dilute solutions must be used and longer periods of sediment-water contact are required before equlibrium can be obtained. This also implies that in the field EC measurement may be misleading as gypsum and calcite particles may be transported as sediment particles rather than in solution.

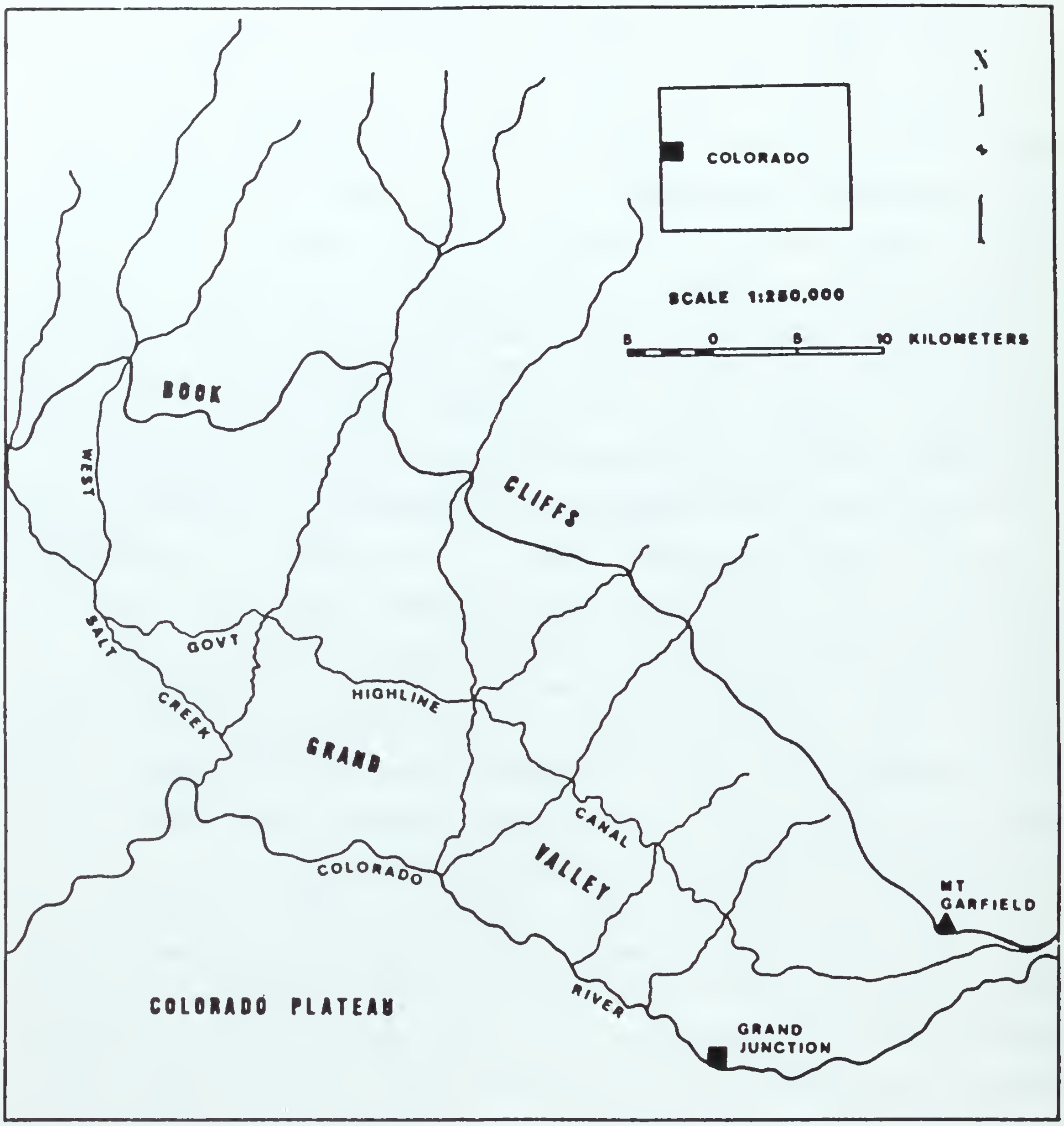
3) GEOMORPHOLOGY OF MANCOS SHALE TERRAIN

The Mancos Shale terrain between Grand Junction, Colorado and Price, Utah, which is the subject of this chapter, is in its simplest form a high escarpment (Book Cliffs) with a pediment at its base. This ideal situation is achieved near Crescent Junction, Utah where the escarpment, capped by Mesa Verde sandstone rises steeply above a southward-sloping pediment. Toward Price to the west and Grand Junction to the east the landforms become more complex as the Green, Price and Colorado Rivers are approached. Elsewhere dissected pediment surfaces are fringed by badlands, and the base of the Book Cliffs is formed by a zone of rugged Mancos-Shale badlands. Often within a short distance, gently-sloping gravel-capped pediments are replaced by steep rapidly eroding badlands.

On a gross scale this variability is revealed by a relative relief map that was prepared by Johnson (1982), in an attempt to show landform distribution on the Mancos Shale outcrop between Grand Junction and the Utah-Colorado boundary north of the Highline Canal (Figs. 3-1, 3-2). As relative relief increases, so does the presence of deeply-incised channels, steep channel gradients, and steep hillslopes all of which signify greater erosion and, therefore, greater salt release. The purpose of the map, then, is to visually distinguish areas according to their relative erosional stability and salt production.

The relative relief map shows clearly the great variability of relief in the study area. Relative relief ranges from 12 m/km^2 along a portion of Big Salt Wash and near East Salt Creek to more than 500 m/km^2 along the Book Cliffs escarpment. The steep terrain of the escarpment is obvious, and there is a 2 to 3 km wide zone along the cliffs which has a relative relief of at least 100 m/km^2. According to this map, the most stable areas are as follows: between Badger Wash and East Salt Creek, along and to the east of East Salt Creek, the area drained by the lower portions of Big Salt Wash and Lipan Wash, along Little Salt Wash, and near Walker Field.

Using available topographic maps, aerial photographs and field reconnaissance Johnson (1982) identified three major landform classes within the area shown on Figs. 3-1 and 3-2. These are badlands, pediments and alluvial valley floors. A similar classification system was developed by Schafer (1981) in the Woodside, Utah area. Johnson



3-1a Location map, Grand Valley, Western Colorado (from Johnson, 1982). Refer to Figure 3.1b for details.

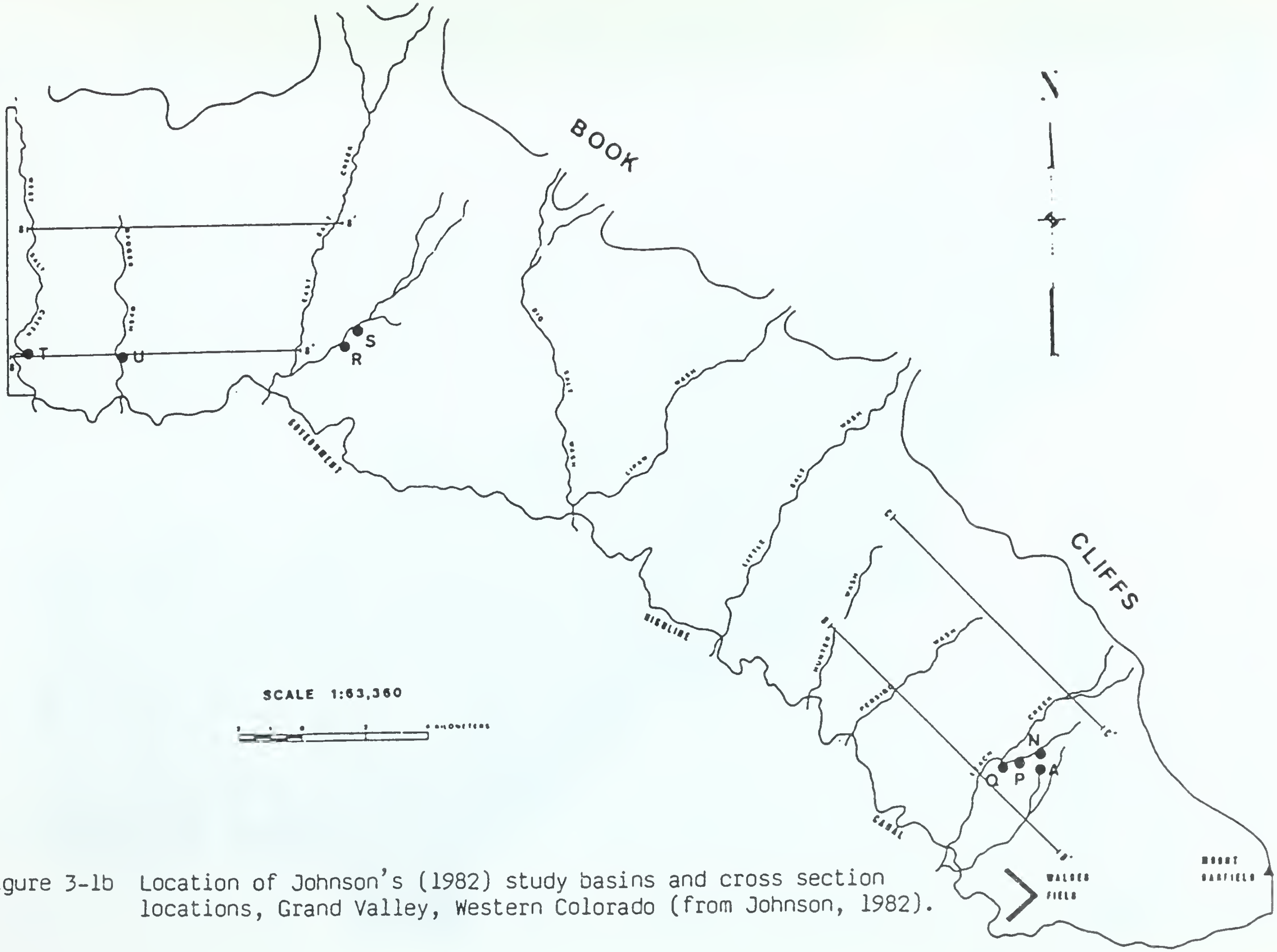


Figure 3-1b Location of Johnson's (1982) study basins and cross section locations, Grand Valley, Western Colorado (from Johnson, 1982).

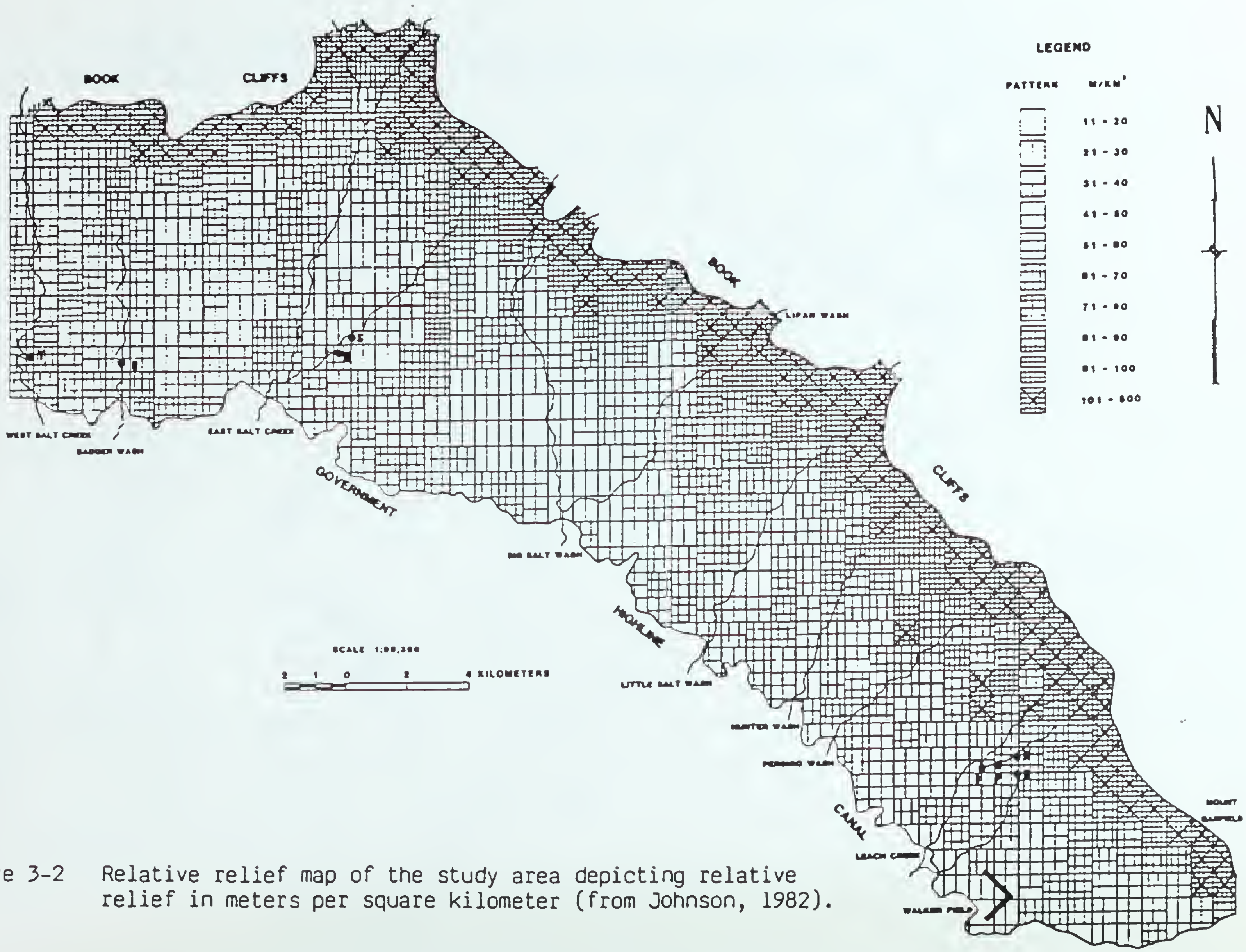


Figure 3-2 Relative relief map of the study area depicting relative relief in meters per square kilometer (from Johnson, 1982).

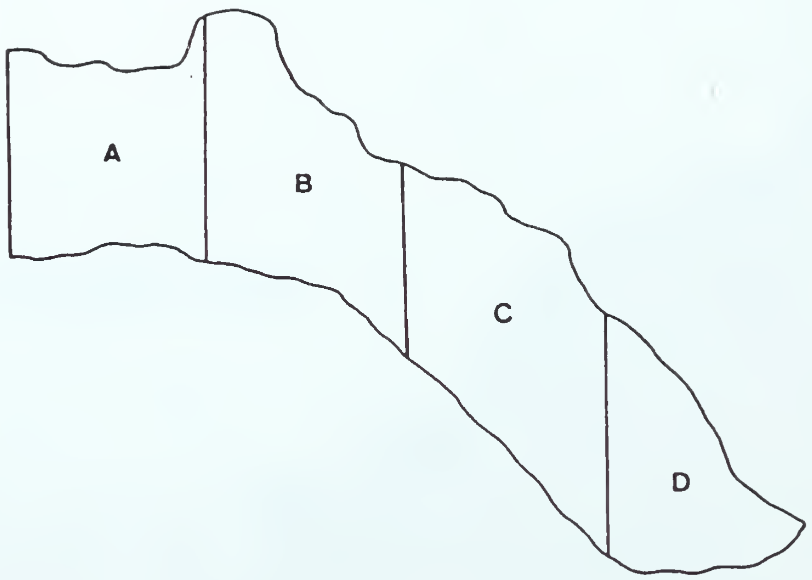
pediments and alluvial valley floors. A similar classification system was developed by Schafer (1981) in the Woodside, Utah area. Johnson prepared a geomorphic map that shows the distribution of these landforms between Grand Junction and the Colorado Utah boundary (Fig. 3-3). The dissected pediments and alluvial valley floors of this three-part classification can be readily identified. However, within the areas designated as badlands there are miniature pediments at the base of eroding hillslopes, as well as small alluvial valleys and incised channels.

Badlands

Badland topography comprises the largest part of the area. The cross sections of Figure 3-4 show the characteristic appearance of this rugged landscape. The badlands have variable relief and high drainage density (Figure 3-4). In fact, three types of channels have developed, and from largest to smallest, they are as follows: 1) upland channels, that originate in the plateau behind the Book Cliffs; 2) channels that extend up to the Book Cliffs; 3) channels that originate on the piedmont at the base of the Book Cliffs. There are of course tributaries to these main channels, and rills develop on the hillsides.

To develop a quantitative description of portions of the badland terrain Johnson (1982) selected 8 small drainage basins for detailed analysis (Fig. 3-5). Basin T is a tributary of an upland channel (West Salt Creek), Basins N, P, and Q drain into a piedmont tributary of Leach Creek, and Basins A, R, S, and U are tributaries to piedmont channels (Fig. 1b). The flow in nearly all channels in the area is ephemeral in response to high intensity summer thunderstorms.

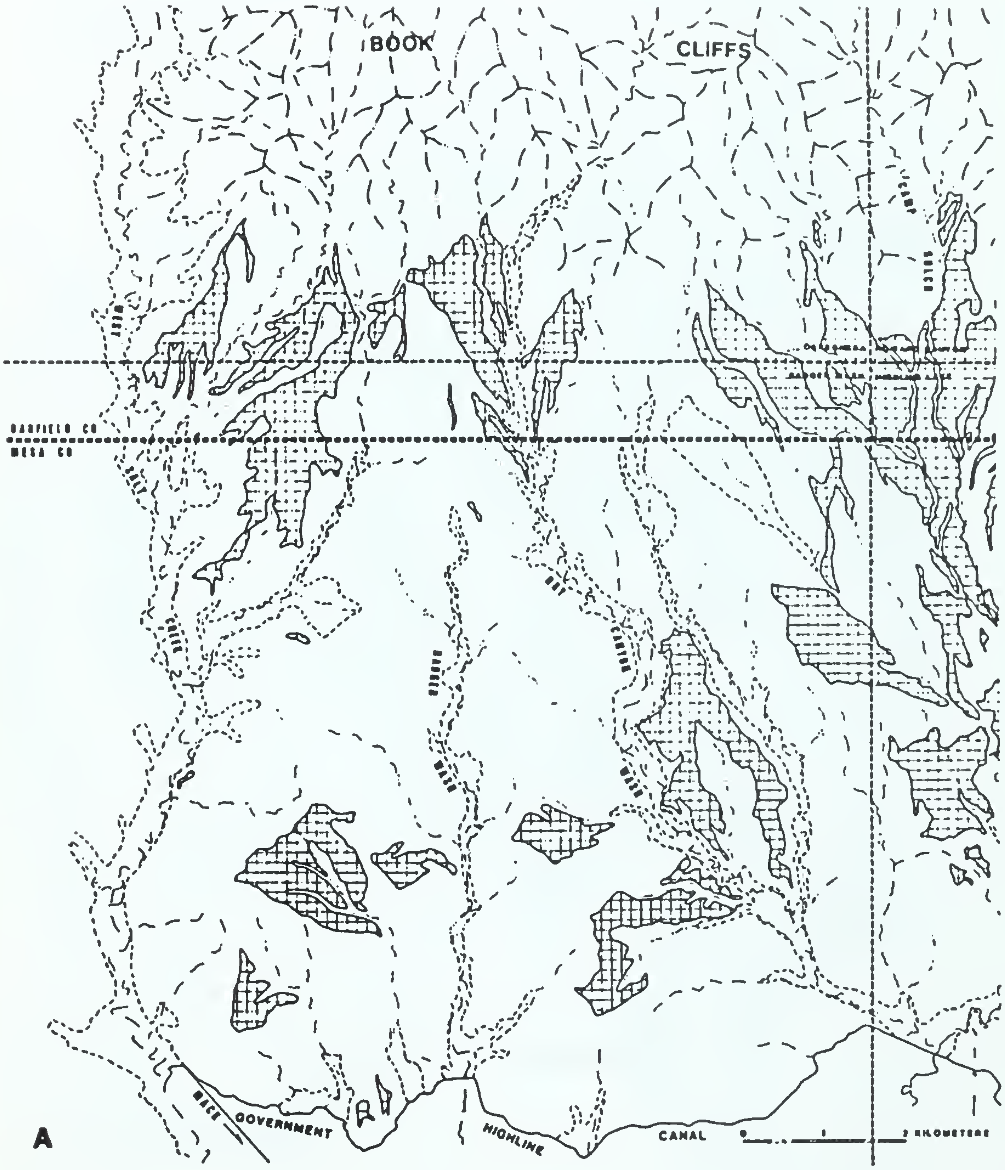
Examination of the tributary basins indicates great variability in inter- and intrabasin characteristics. In all cases, basin length is greater than basin width, but basin size, shape, and relief vary widely. Basin area ranges from 22,000 m^2 for Basin Q to 340,000 m^2 for Basin T (Table 3-1). Relief varies from 15.2 m to 84.7 m for Basins Q and T, respectively. The lowest relief-length ratio occurs for Basin S with a value of 0.052, while the highest is for Basin U with a valve of 0.097. Basin P has the lowest main channel gradient (3.64%) and Basin U the



LEGEND

- GRAVEL-CAPPED PEDIMENT SURFACES
- BOUNDARY BETWEEN ALLUVIAL VALLEY FLOORS AND BADLANDS
- EPHEMERAL STREAM CHANNELS
- PERENNIAL STREAM CHANNELS
- BOUNDARY OF THE BOOK CLIFFS
- DRAINAGE DIVIDES ON THE ESCARPMENT OF THE BOOK CLIFFS
- BOUNDARIES OF TOPOGRAPHIC QUADRANGLES

3-3 Landforms map of Mancos Shale terrain between Book Cliffs to the north, Highline Canal to the south, Mt. Garfield to the east and West Salt Creek to the west (from Johnson, 1982). Note: map is in four parts (i.e., A,B,C,D).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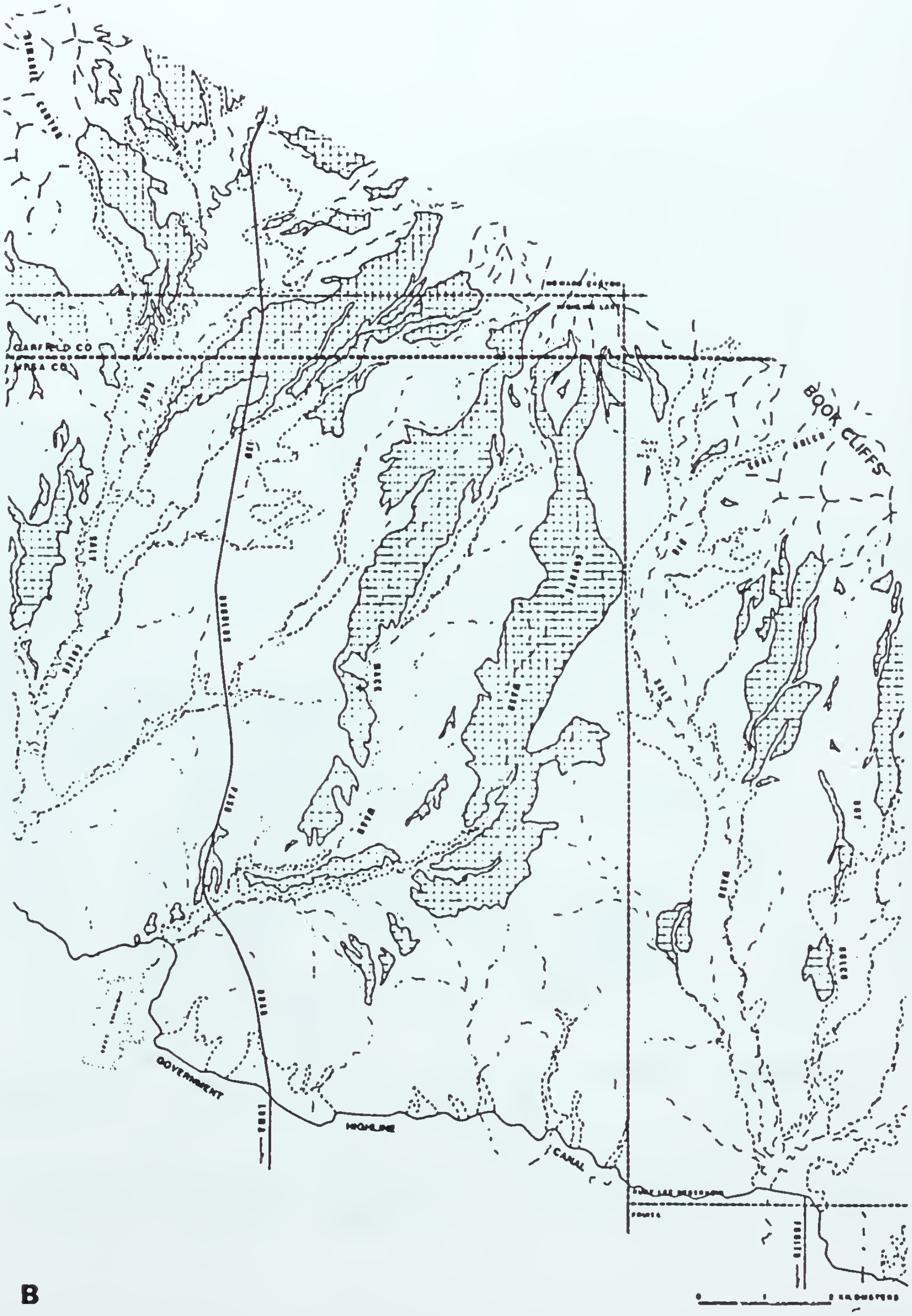

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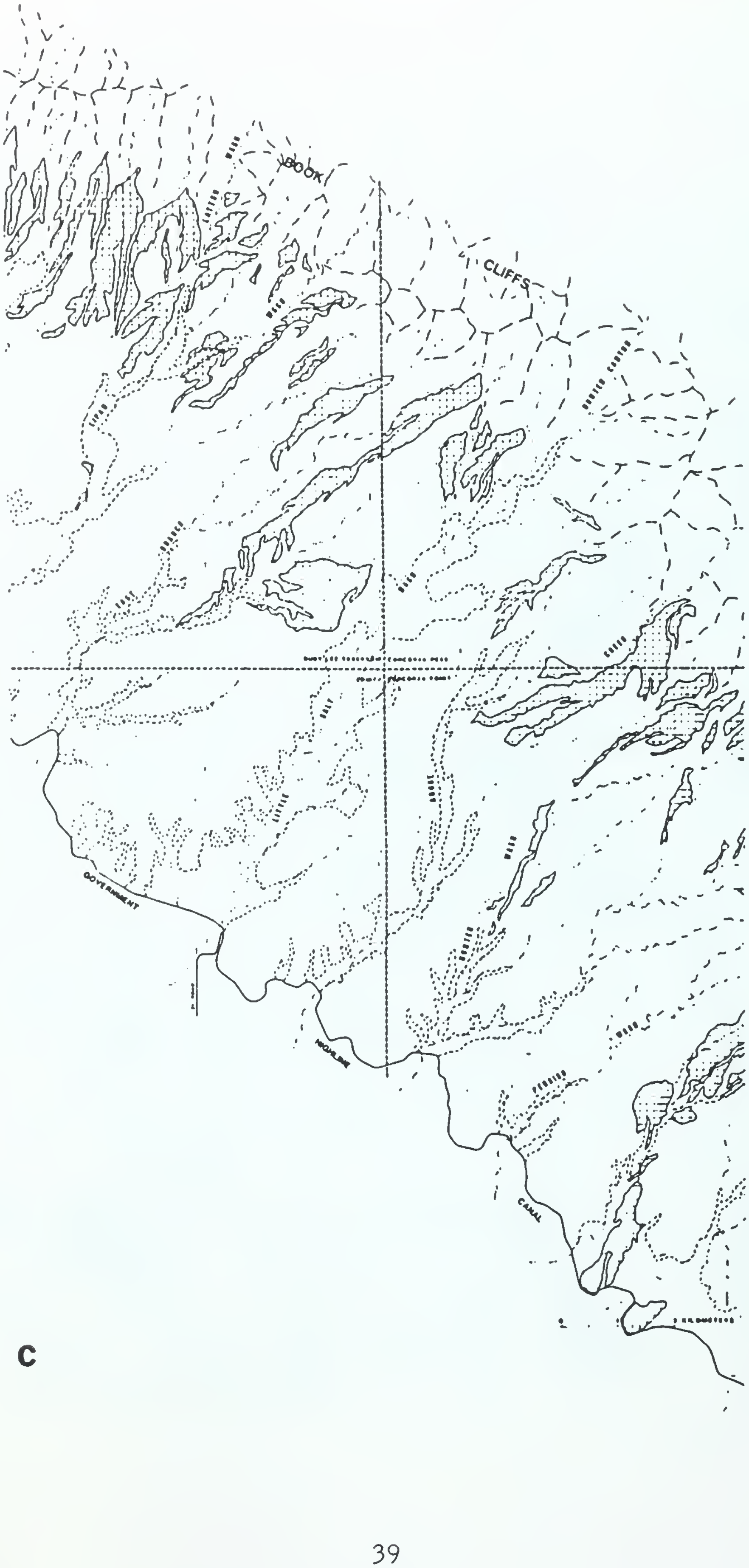

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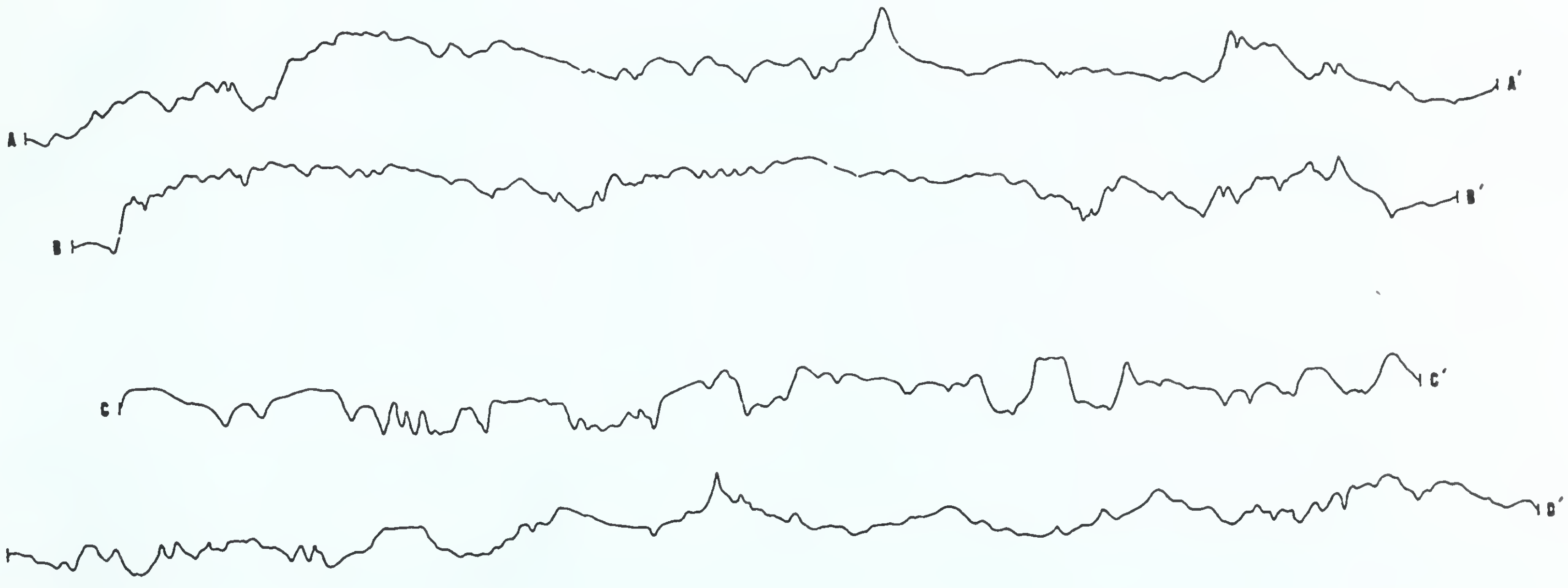
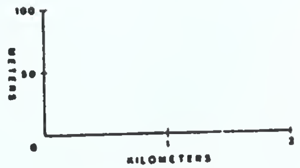
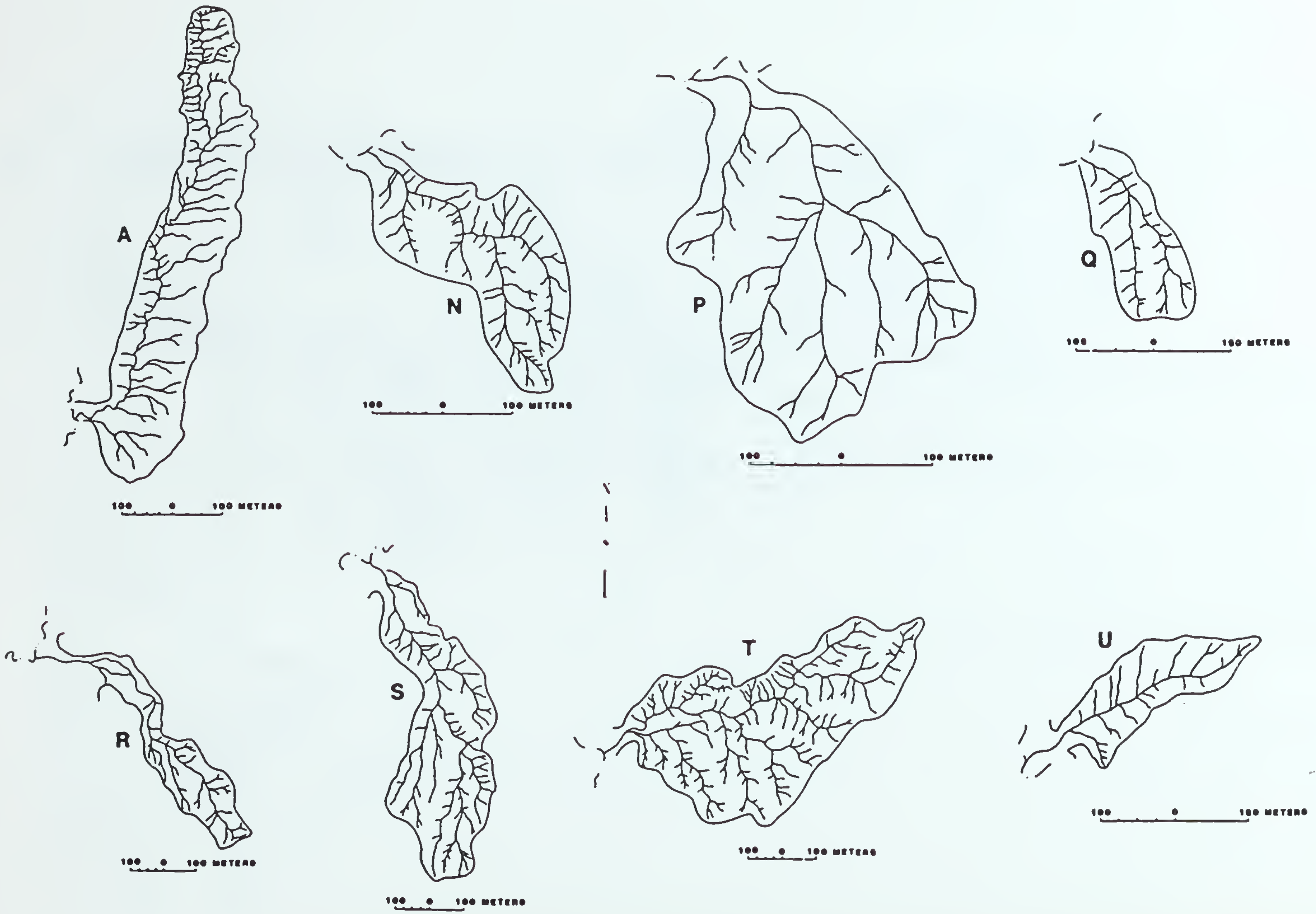




3-4 Cross sections (from Johnson, 1982). Refer to Figure 3.1b for locations.



3-5 Maps of eight drainage basins in Grand Valley, Western Colorado (from Johnson, 1982). Refer to Figure 3.1b for drainage basin locations.

Table 3.1. Measured drainage basin characteristics (from Johnson, 1982).

Basin	Area (m^2)	Relief (m)	Basin Length (m)	Maximum Basin Width (m)	Relief Ratio	Length/Width	Avg. Gradient of Main Channel (%)
A	250,000	76.2	900	165	0.085	5.45	4.11
N	44,300	32.3	420	150	0.077	2.80	6.56
P	78,000	22.6	410	280	0.055	1.46	3.64
Q	22,000	15.2	240	100	0.063	2.40	5.46
R	105,000	56.1	860	180	0.065	4.78	4.84
S	240,900	48.8	945	310	0.052	3.05	3.95
T	340,300	84.7	1000	455	0.085	2.20	5.68
U	32,000	34.1	350	90	0.097	3.87	7.38

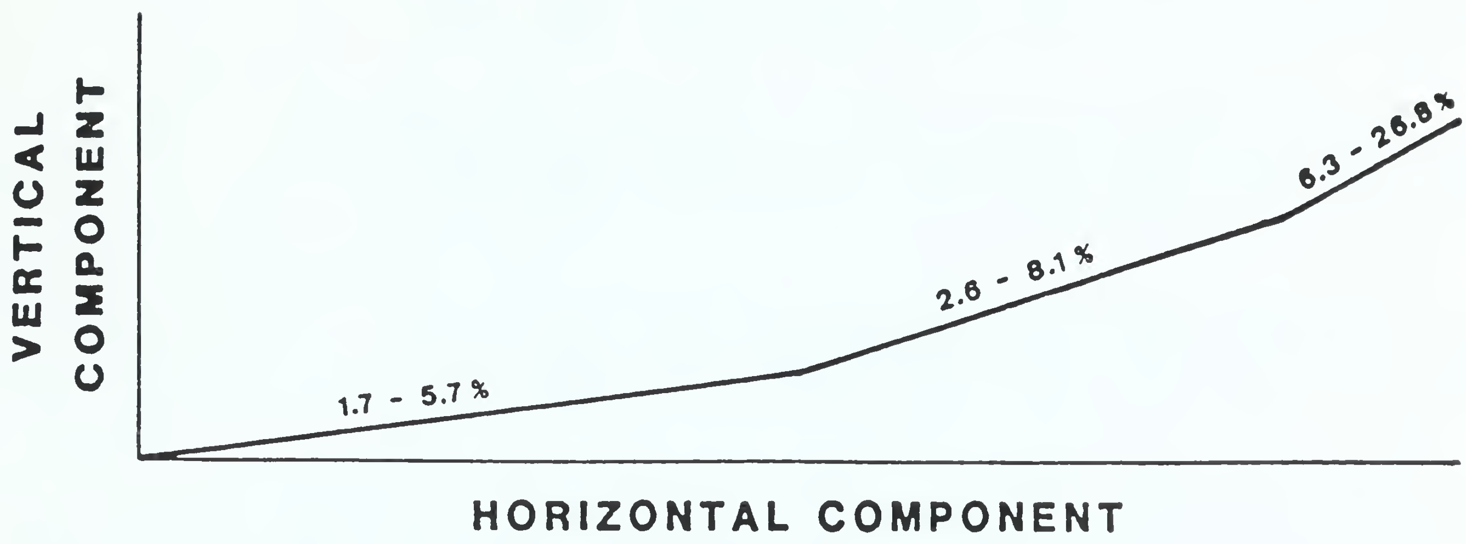
type of master channel into which they drain, the variable composition and erosional resistance of the bedrock, and local effects due to aspect. Field observations indicate that all channels in the study basins are incising.

Hillslopes

Hillslopes were studied by measuring valley cross sections within the eight basins (Fig. 3-6). There is a wide range of hillslope gradients within basins and between basins (Table 3-2). Although hillslope gradients differ widely, characteristic hillslope shapes are evident (Fig. 3-7). Convex hillslopes are characteristic of the upper portions of all the basins (Fig. 3-7a). Figure 3-7b illustrates convex concave slopes that occur in the middle portions of all the basins. The convex-concave hillslopes alternate on opposite sides of the valleys. This alternation appears to be controlled by the meandering channel configuration at the slope base as opposed to control by either rock type, rock structure, or aspect. Finally, concave slopes are found near the mouths of all of the basins Fig. 3-7c).

Soil depths were measured in six of the eight basins. Soil depth is the thickness of the layer of residual material derived from underlying weathered, yet structurally distinct, bedrock. The soils are derived from two lithologies in the Mancos Shale, shale and sandy shale. Field observations indicate that portions of the badlands are underlain predominantly by shale, of which Basins A, N, and Q are examples. Basins S, T, and U are underlain by interbedded shale and sandstone. Soil texture analyses by Lusby, et al (1963) show that soils derived from shales are clay-rich, while soils derived from interbedded shale and sandstone are mixtures of clay and sand.

An analysis of variance was conducted to compare the means of soil depth for divides and hillslopes within each basin. In five of the six basins, there is no significant difference in soil depth between divides and hillslopes. Therefore, the divides and hillslopes apparently have equal rates of soil development and/or erosion. However, Basin U is an exception where soil depth is significantly greater on the divides than on the hillslopes. Soil depths are the same in basins of the same lithology, but the mean soil depth for basins underlain by interbedded

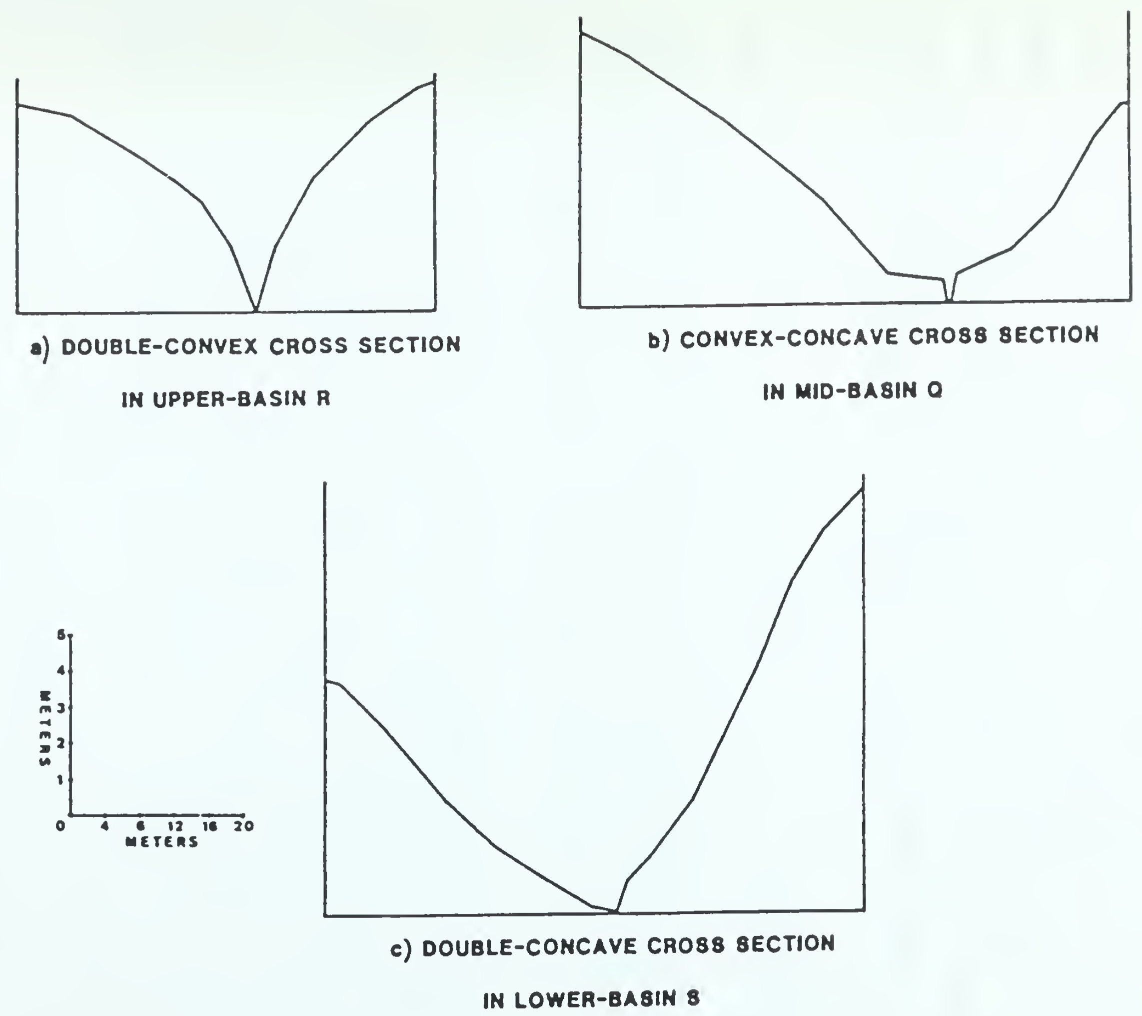


3-6 Typical main channel longitudinal profile and ranges of channel gradients (from Johnson, 1982).

Table 3.2. Hillslope gradients (from Johnson, 1982).

Basin	Location	n	Avg. (%)	Min. (%)	Max. (%)
A	main channel	6	27.0	9.5	42.9
A	tributaries	14	31.4	11.1	53.6
N	main channel	7	26.5	14.0	41.9
N	tributaries	10	32.4	14.3	46.8
P	main channel	8	16.0	9.3	29.1
P	tributaries	4	16.3	13.0	21.8
Q	main channel	2	22.5	19.3	25.7
Q	tributaries	8	22.1	16.8	26.3
R	main channel	10	28.7	16.5	40.7
R	tributaries	12	27.5	20.1	40.6
S	main channel	12	24.0	15.3	44.3
S	tributaries	8	23.8	16.7	29.5
T	main channel	9	29.0	19.4	45.9
T	tributaries	12	38.3	23.9	50.0
U	main channel	6	25.8	11.9	36.2
U	tributaries*	--	--	--	--
all	main channels	60	25.2	14.4	38.3
	tributaries	68	29.2	16.6	38.4
	average		27.3	15.4	38.3

*no major tributaries



3-7 The three types of valley cross sections present in the measured drainage basins (from Johnson, 1982). a) convex slopes in Basin R, b) convex-concave slopes in Basin Q, C) concave slopes in Basin S.

shale and sandstone is significantly greater than the mean soil depth for basins underlain by shale. The explanation for this is probably the lower erodibility of sandy soils, their greater infiltration rates and better vegetative cover (Lusby et al, 1963).

Hadley and Lusby (1967) emphasize the importance of hillslope aspect on soil depth and hillslope erosion. That is, since the north-facing slopes are colder and retain more moisture, they are expected to have deeper soil development and shorter, steeper slopes than the south-facing slopes. However, Johnson's (1982) field observations suggest that aspect plays a relatively minor role in the geomorphic processes of the area.

Geomorphic Stability

Generally, the badlands are areas of rapid erosion. Where rills and channels are steep, they are efficient conduits for runoff and sediment transport. Many badland basins are undergoing active erosion due to the combined effects of rill development, soil creep, and bank failure. However, sediment yields can be highly variable depending on drainage basin morphology and the potential for storage of sediment within the drainage basins. Certainly large areas that have been classified on badlands may produce relatively small amounts of sediment. In relative terms, badlands underlain by interbedded shale and sandstone bedrock are more stable than those underlain by shale bedrock. The former are less erodible because they have a more permeable soil layer which gives rise to deeper soils and greater, though minimal, vegetative cover than the latter.

Pediments

Johnson's (1982) study area includes many smooth, gently sloping, gravel-capped landforms that rise above the badlands. These features are common along other portions of the Book Cliffs as well as in other areas where Mancos Shale crops out below resistant cliffs. These landforms are pediment remnants. By definition, a pediment is a gently inclined planate erosion surface carved in bedrock and generally veneered with fluvial gravels (American Geological Institute, 1976).

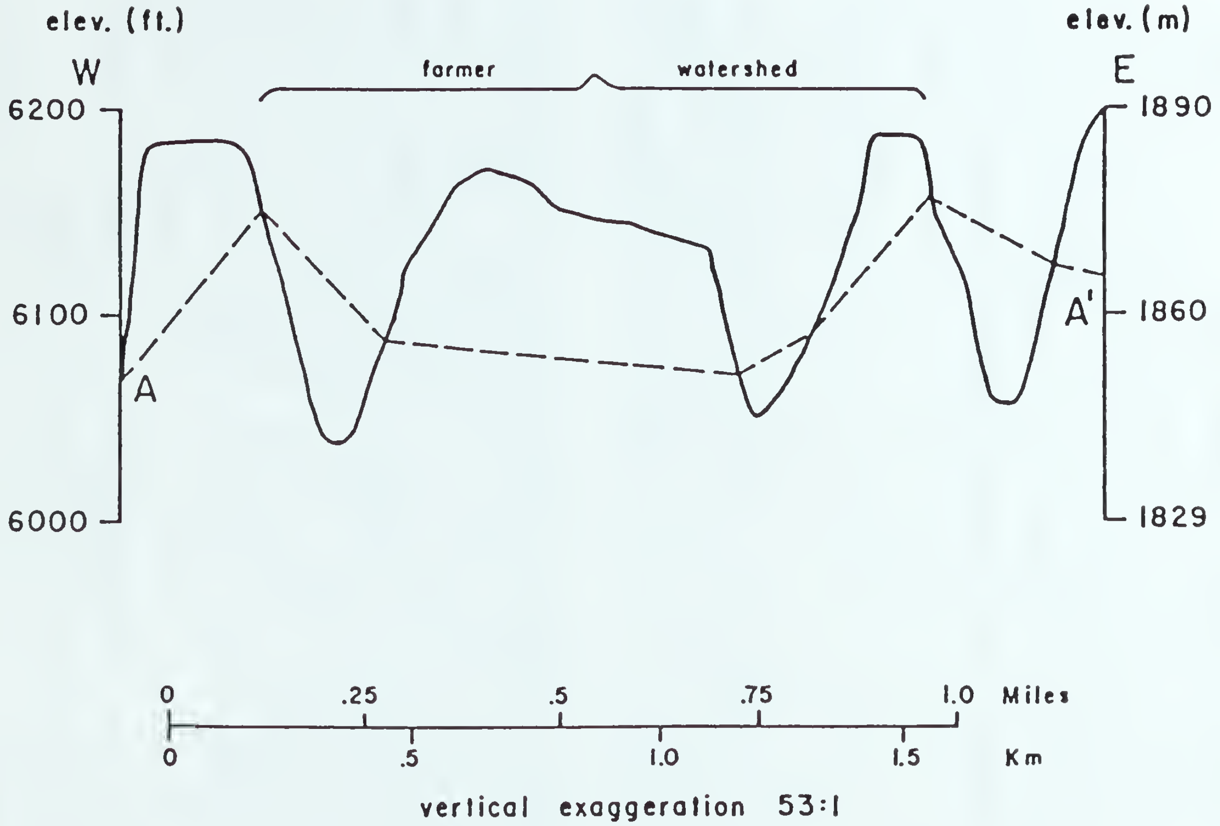
Prominent pediment remnants dominate the Book Cliffs piedmont. They radiate away from canyon mouths in roughly fan-shaped patterns. The highest remnants tend to have a long, narrow, sometimes sinuous shape in plan view. The lower-lying remnants, which may not have been subject to dissection for as long as the higher remnants, retain a fan shape. At places near Grand Junction and Price there are as many as 5 levels of pediment remnants preserved above the streams draining from the Book Cliffs. The average gradient of pediments in the Price area is 4%.

The smooth gently sloping surfaces that sweep away from the Book Cliffs convey an impression that the bedrock-gravel contact is also a smooth plain, but in fact the gravel thickness is highly variable and the bedrock surface is very irregular (Fig. 3-8). Apparently the irregular Mancos Shale surface was either buried by debris flows that were triggered by mass failure of the Book Cliffs during periods of higher precipitation or stream capture rejuvenated drainage basins which provided large amounts of gravel that buried the irregular topography of the piedmont badlands to form the smooth gravel surfaces of the pediments.

Up to 40 m of partially cemented calcitic alluvium caps the pediment remnants. This alluvium contains some extremely coarse gravel which is derived from the Mesa Verde Group, and it is mixed with finer sediment from the Mesa Verde and younger formations. There are boulders as large as 5 m in maximum diameter and in one sample locality, the mean diameter of the ten largest clasts was 1.95 m. One or more zones in these gravel caps are cemented by calcite, so that the gravels act as a caprock protecting the underlying Mancos Shale from erosion. Surrounding and encroaching upon the pediment remnants are active pediments that are currently forming. Rills, sheetwash and creep also erode the pediment-remnant side slopes undercuting and reducing them in area.

Geomorphic Stability

Pediments are relatively stable surfaces. Their surface slopes are too gentle for rill formation, and the gravel cap acts as a protective armor. They support a much greater vegetative cover than the badlands, due in part to deeper soil development and higher infiltration rates than in the badlands (U.S. Bureau of Land Management, 1978). However,



3-8 Cross section of dissected pediment remnants near Soldier Creek. The dotted line represents the inferred bedrock surface between surveyed gravel - bedrock contacts. The solid line represents the present ground surface (from Carter, 1980).

the margins of the pediments are being dissected to form narrow belts of badlands. Also, some of the pediment surfaces are partially dissected by headward eroding channels. The channels erode headward when sheetwash from a thunderstorm cascades from the pediment surface into the channel.

Alluvial Valley Floors

Alluvial valley floors are the least abundant landform in the study area. All upland, cliff, and piedmont channels contains alluvial deposits, as do most tributaries. At present, all channels are incised. All of the measured channels, with the exception of those in Basins A and U, which contain no alluvium, are incised into alluvium near their mouths. The alluvial valley floors, measured along the channels, have gradients ranging from 2.0 to 3.3 percent. The alluvium contains abundant imbricated chips of shale and/or sandstone, depending on the local bedrock.

The gradients of the alluvial valley floors cannot be explained merely by the high sediment load of the runoff. For sediment to be deposited at such steep gradients, a sudden change in channel gradient and associated loss of energy are required. The alluvium can be best explained by backfilling following a decrease in channel gradient downstream.

Schneider (1975) studied the subsurface geology and Quaternary deposits of Grand Valley near Fruita, Colorado. He concluded that the Colorado River gradually shifted south without appreciable downcutting, and this significantly reduced the gradients of the tributary channels in this area. The high sediment loads could not be transported at lower gradients. As a result, fan-like deposits formed along the Book Cliffs in the present Grand Valley agricultural area, and there was backfilling of the tributary channels in the badlands. The channels then became graded to the slope determined by the present position of the Colorado River.

The suggested sequence of events regarding the evolution of alluvial valley floor surfaces is as follows: 1) all channels were once bedrock channels; 2) the channels were aggraded during a long, continuous period of backfilling after the Colorado River shifted to the south; and 3) the channels begin incising due to man-activated headward gully erosion (Fig. 3-9). All of the channels south of the Highline Canal have been altered by land use, including straightening to increase agricultural land area and modification by irrigation return flow. The increased erosive energy resulting from both alterations cause gully erosion. The present condition of general channel incision in the study area appears to be, at least in part, a result of agricultural practices downstream of the Highline Canal.

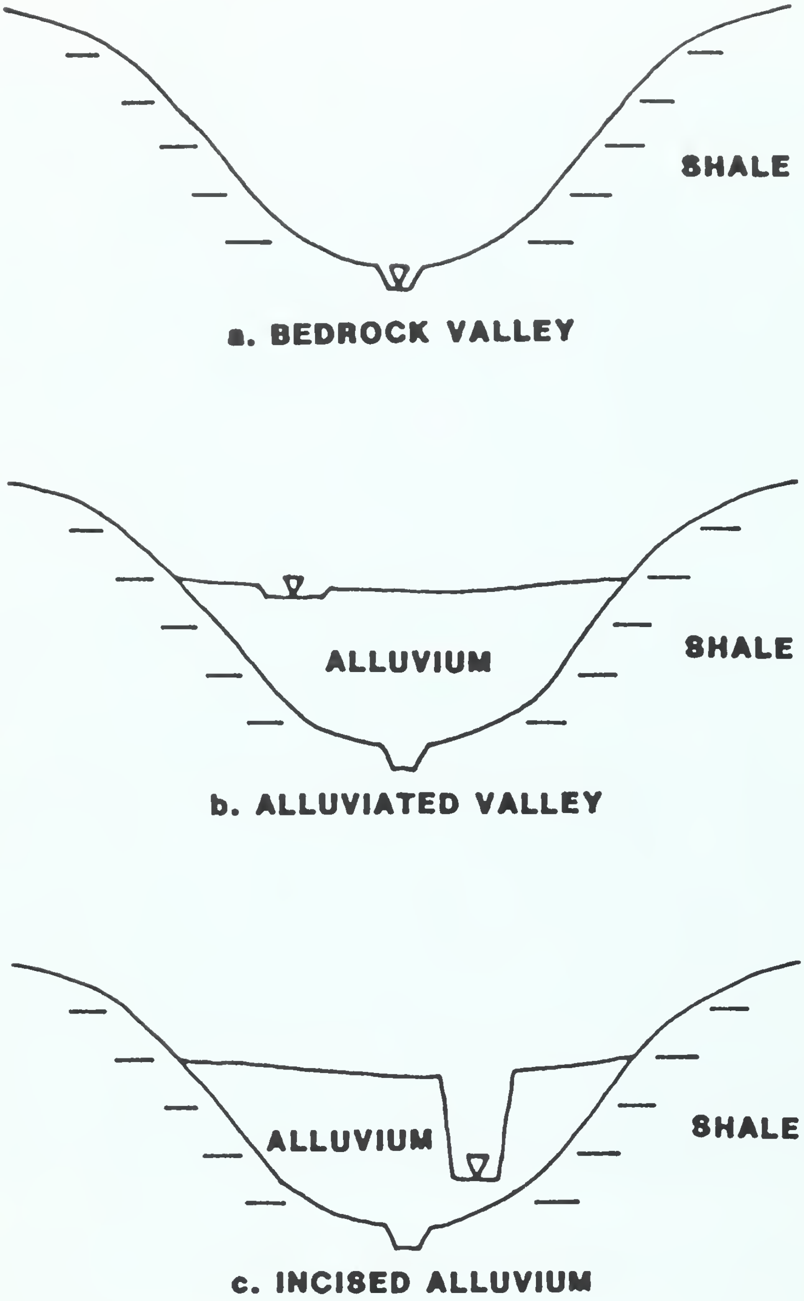
Geomorphic Stability

In the larger valleys, the alluvial surfaces are stable except along the channels, which in some places have arroyos as much as 10 m deep. The near-vertical arroyo walls are susceptible to undercutting and caving of bank material. The valley floors are unstable because they have been incised and unless the incised channels aggrade, the potential for removal of the alluvium is great. However, the surfaces not directly affected by the arroyos generally support a good cover of grasses and shrubs, and they are not eroding significantly at present.

Summary

The three major landforms that comprise the Mancos-Shale terrain are badlands, pediments, and alluvial valley floors.

The badlands in Johnson's (1982) study area comprise the largest area, and they are the most erosionally unstable of the three landforms. The pediments are being reduced in size, as a result of badland encroachment and channel incision. The actual pediment surfaces, however, are gently sloping and erosionally stable. Alluvial valley floors have been incised, and the potential for removal of the remaining alluvium is great. Nevertheless, the surface of the alluvium is not eroding because, like pediments, their surfaces are too gentle for rill development. Salts have been leached out of the alluvium and therefore their erosion will produce less salt than the erosion of badlands or pediment. However, channels incised into alluvium incorporate both sediment and salt from sloughed channel banks and salt from evaporite crusts exposed at alluvium-bedrock contacts. Elsewhere the degree of valley floor incision may be much less than in the Grand Valley area and the valley floor may be relatively more stable.



3-9 Proposed valley evolution in the study area: a) Bedrock Valley before the southward shift of the Colorado River; b) aggradation of the Bedrock Valley by back-filling after the southward shift of the Colorado River; and c) channel incision probably due to downstream land use practices (from Johnson, 1982).

The relative relief map (Fig. 3-2), although it shows the variability of relative relief, does not identify specific locations of erosional instability. The landforms map (Fig. 3-3), on the other hand, outlines the three major landforms in the area thus differentiating the erosionally unstable and greater salt-producing badlands and alluvial valley floors from the pediment surfaces. Similar maps for other Mancos Shale areas can provide the basis for identifying those areas that require the greatest attention from the land manager. As will be shown later (Fig. 5-19) sediment yield is more a functin of drainage basin slope (relief ratio) than land form type.

4) VARIABILITY OF SALINITY IN DIFFUSE-SOURCE AREAS

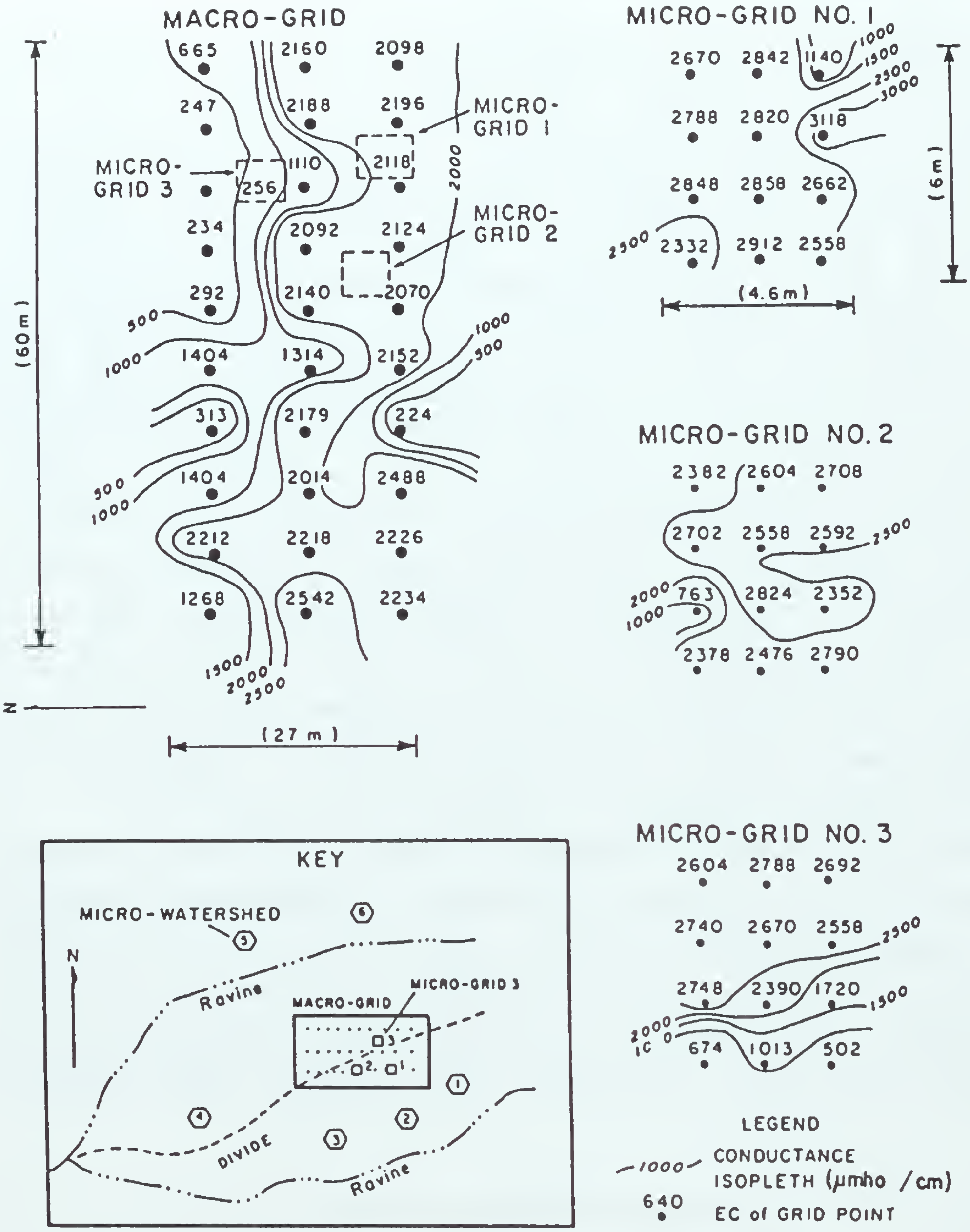
The variability of SMC in surficial Mancos Shale and alluvium is known to be very high (Ponce, 1975; Laronne, 1977; White, 1977). A large spatial variability of physical and chemical properties of surficial materials is not uncommon. Becket and Webster (1971) reviewed the literature on soil variability and stated that because the required collection and analysis of a large number of samples is laborious and not very glamorous, little information is available on how much variability is present in soils. They conclusively showed that variability increases with an increase in area, and they maintained that this increase is due to the inherent spatial variability in parent materials (e.g. localized mineralization), microclimate (e.g. shelter in depressions), topography (e.g. aspect and formation of catenas), within-soil processes (e.g. leaching) and biological activity (e.g. burrowing animals). They concluded that as much as half of the variability (expressed by the coefficient of variation) present within one hectare is already present within a few square meters. Vegetation also concentrates salts (U.S. Bureau of Reclamation, 1984, Table 7).

It should be noted that outcrops of Mancos Shale and associated alluvium are not the only large contributors of diffuse-source salinity within the Upper Colorado River Basin. For instance, most of the Green River formation is saline, and its chemistry and SMC have been shown to differ markedly with lithology and location (Ward, Margheim and Lof, 1971; Schmehl and McCaslin, 1973; Cook, 1974; Margheim, 1975; McWhorter, 1980).

Surface Variability of SMC

Ponce (1975) examined the spatial variability of SMC in the surface layer of Mancos Shale. He found that the range of EC values decreases as the sampled area decreases, owing to the greater homogeneity of lithology, weathered products, aspect and moisture content at a given locale (Fig. 4-1).

Ponce (1975) obtained EC values from 1:1 extracts, but EC values from more dilute solutions would be expected to show a larger range



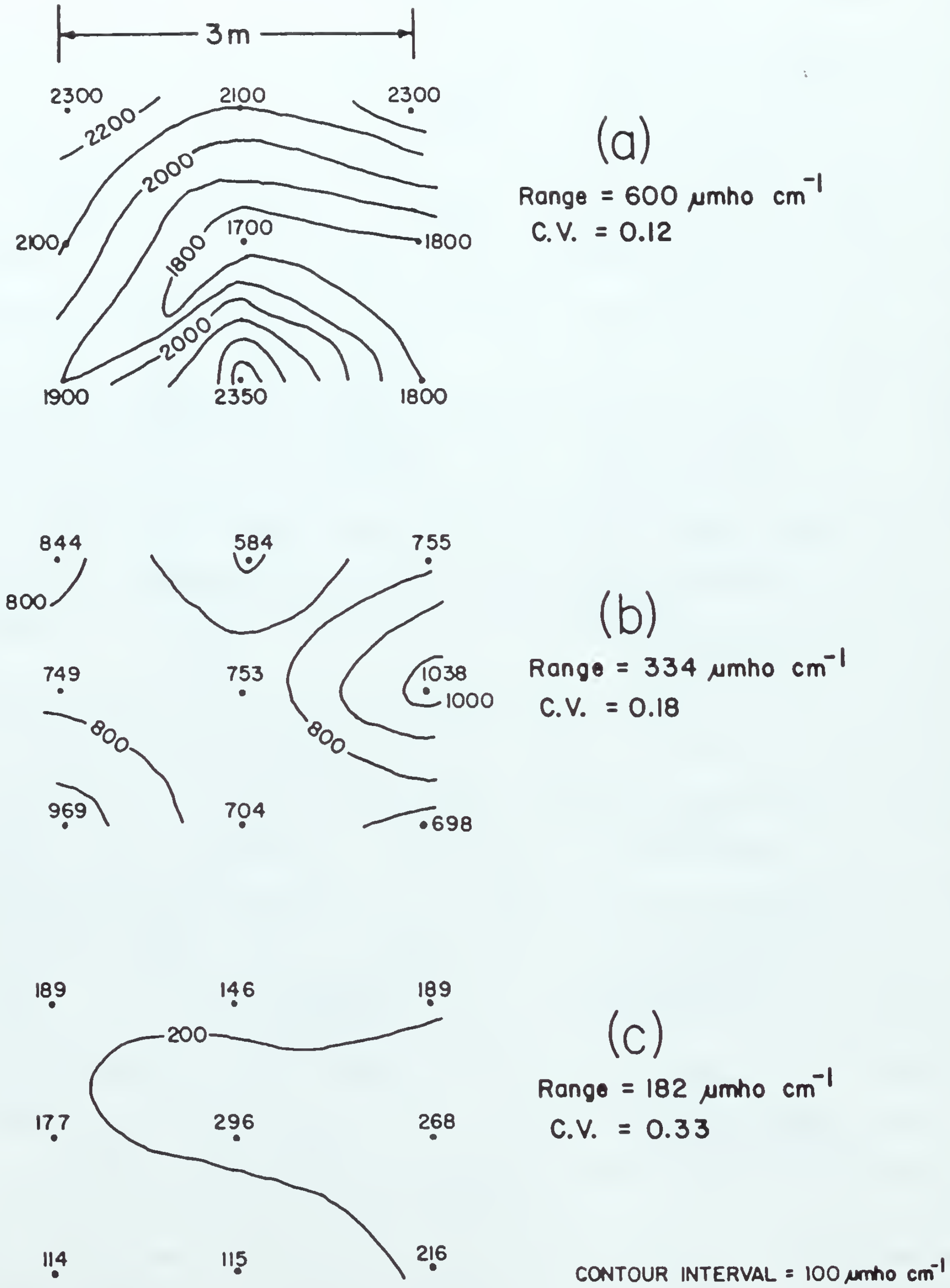
4-1 Spatial variation of EC derived from 1:1 sediment-water mixtures of the surface crust of Mancos Shale in the Price River Basin (after Ponce and Hawkins 1978).

because EC is proportional to the sediment-water ratio (Chapter 2). The relative variability of EC, as described by the coefficient of variation, should increase with an increase in sediment-water ratio because the aqueous solution is not saturated with respect to specific compounds at low sediment-water ratios. This effect on spatial variability is demonstrated by the EC of samples obtained in Mesa Creek, a small tributary of McElmo Creek, Colorado. The EC of nine samples was measured at three sediment-water ratios (1:1, 1:9, 1:99) and contour plotted to show the increase in variability of EC with an increase in sediment-water ratio (Fig. 4-2).

White (1977) also conducted an investigation of spatial variability of SMC. The results (Fig. 4-3) demonstrate the large inherent variability of SMC on the surface of a Mancos Shale channel bank in the Price River Basin, Utah. These and previous results show that the surface layer of Mancos Shale and associated alluvium contain an appreciable quantity of soluble minerals, and that this quantity varies spatially to a great extent.

Not only do the different shale formations have different inherent characteristics, but Mancos Shale, the prime contributor of salinity, also differs from deposits closely associated with it. For instance, Laronne (1977) demonstrated that monovalent and divalent ions forming highly-soluble sulfates are considerably more abundant in Mancos Shale than in leached Mancos Shale alluvium (Fig. 4-4). Furthermore, the Mancos Shale is subdivided into stratigraphic members in several geographic locations (Hunt et al, 1953; Stokes and Cohenour, 1956). Ponce (1975) has demonstrated that the members of the Mancos Shale differ with respect to SMC (Fig. 4-5) and their potential for salinity contribution. Similar results were also obtained by White (1977).

That shales of different stratigraphic units differ in SMC, and that SMC varies within a small area is not surprising to pedologists and geomorphologists. A soil survey conducted primarily in the Price River Basin has demonstrated that SMC, and other chemical and physical characteristics vary significantly with soil associations (Thorne et al, 1967). Soil associations in the Upper Colorado River Basin differ with respect to various characteristics, including SMC, as attested by



4-2 Spatial variation of EC in the surface (0-13 cm) of alluvial bed material in Mesa Creek. EC was derived from nine samples at 1:1(a), 1:9(b) and 1:99(c) sediment-water mixtures (C.V. = coefficient of variation).

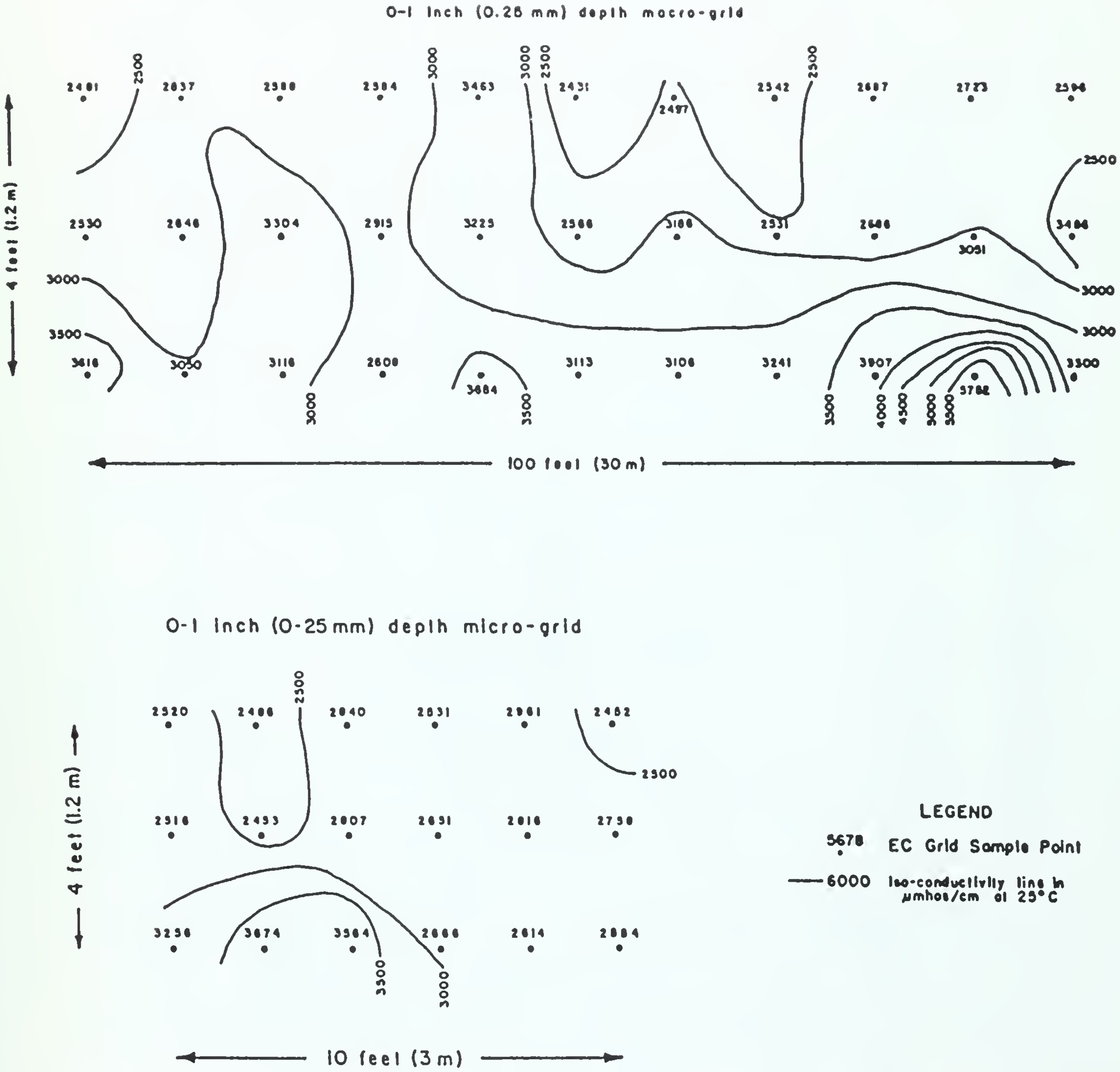
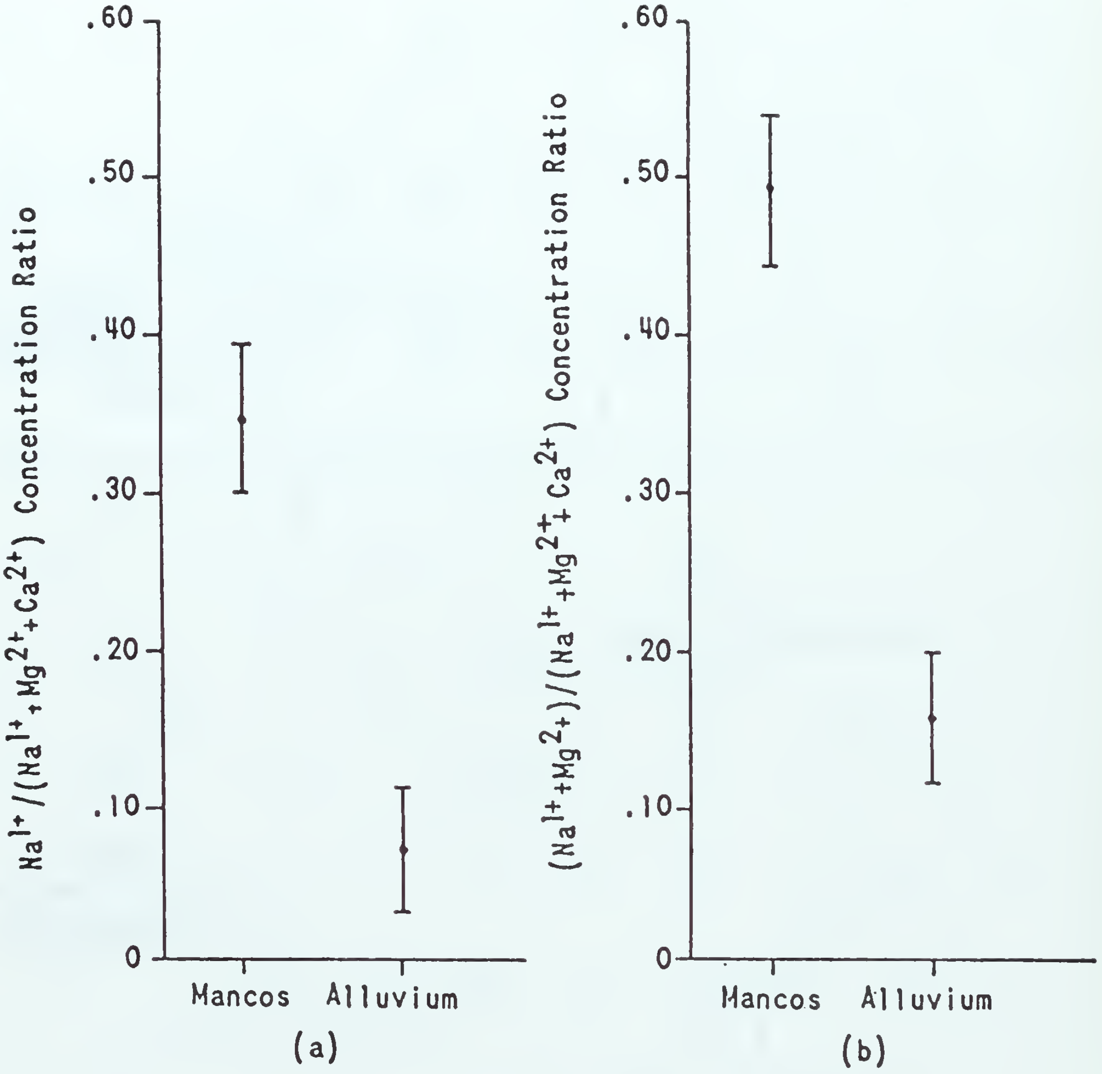
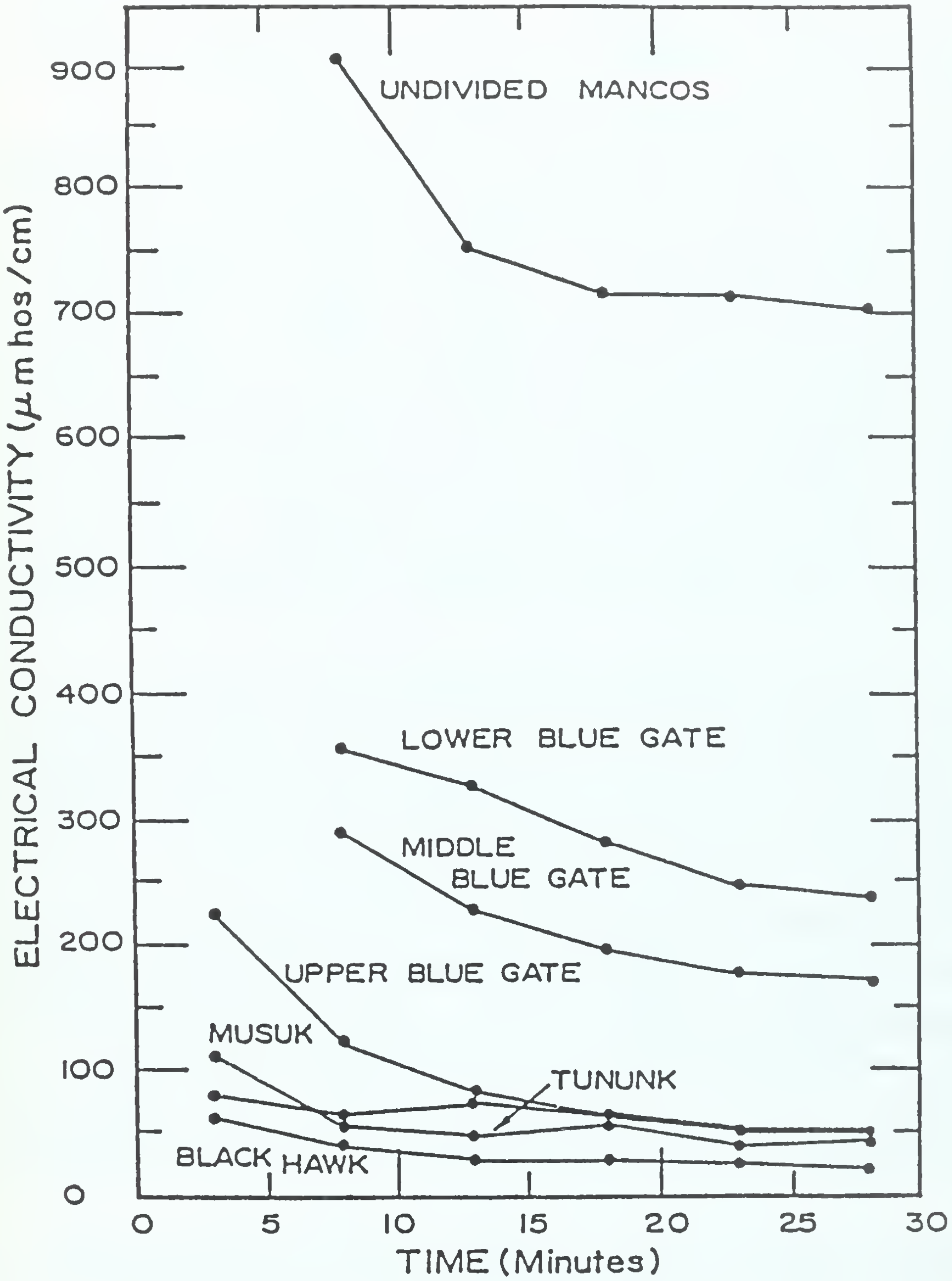


Figure 4-3 Spatial variation of EC of 1:1 sediment-water mixtures of a Mancos Shale channel bank in the Price River Basin, Utah (after White, 1977).



4-4 Means and 95 percent confidence intervals about the means of Na^{1+} (a) and $NA^{1+} + Mg^{2+}$ (b) abundance ratios from 1:99 solutions of Mancos Shale and alluvium (after Laronne, 1977).



4-5 Mean EC of generated runoff for plots on selected stratigraphic members of Mancos Shale in the Price River Basin. Time is from the beginning of rainfall (after Ponce, 1975).

several additional soil surveys (Knobel, Dandsdill and Richardson, 1955; Cline et al, 1967; Hunter and Spears, 1975), and by Laronne and Schumm's (1977, 1982) study of lithomorphologic units along reaches of West Salt Creek, North Miller Creek and Mesa Creek (see Fig. 4.2).

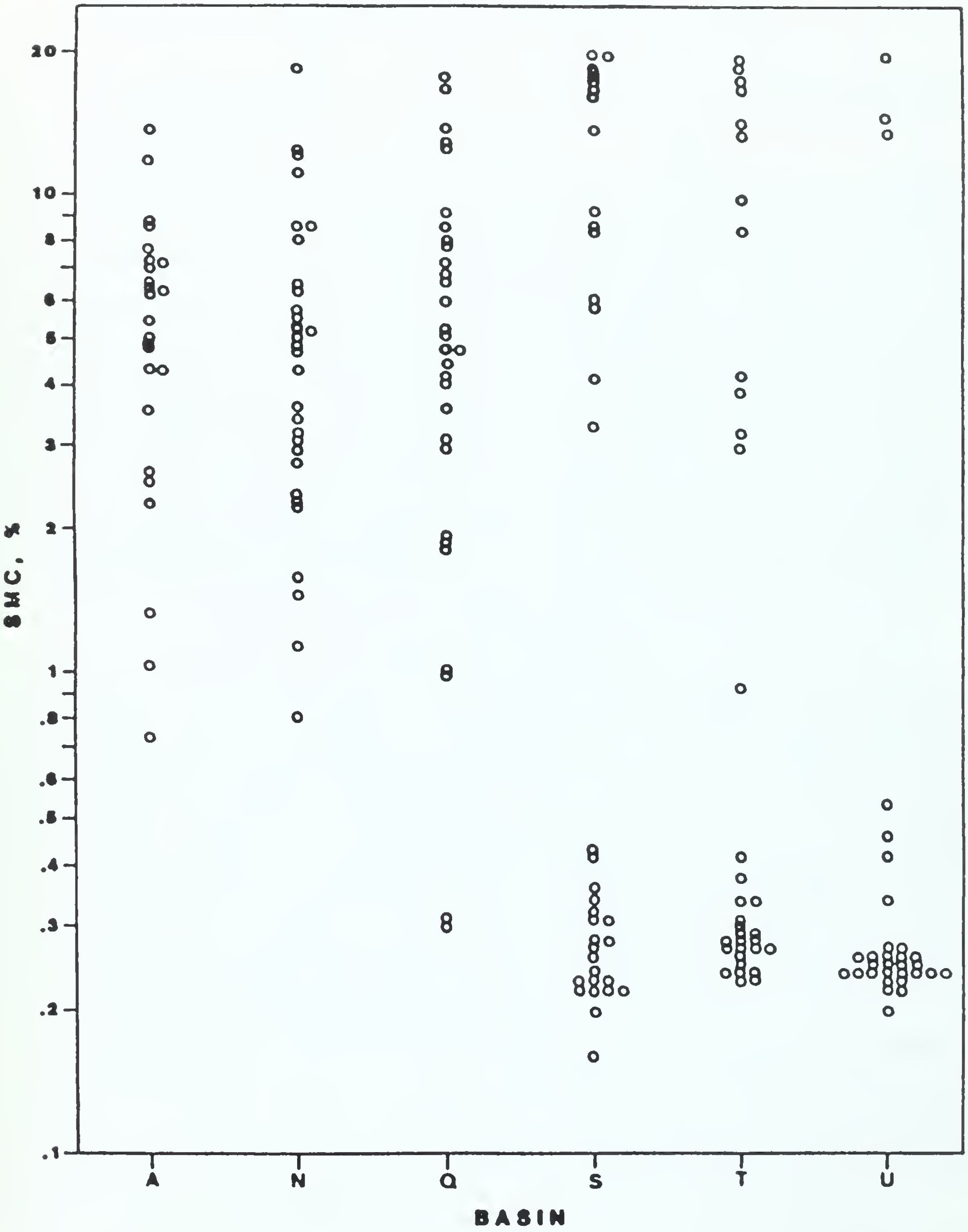
Differences in SMC between sampling units can be masked by the large inherent variability in SMC. Nevertheless an analysis of variance of the mean SMC for all sampling units (excluding Mancos Shale hillslopes), for each river basin and for all basins together reveals that a difference between them does exist in several cases. Notwithstanding the large variability in SMC, comparing individual sampling units by pairs shows significant differences (at a confidence interval of 95 percent about the means) in SMC between alluvium (West Salt and North Miller Creeks) and Mancos Shale bedrock and hillslopes. The hillslopes are significantly more saline than any other unit except efflorescent crusts.

Johnson (1982) also evaluated the variability of salinity in 6 of his 8 badland drainage basins (Fig. 4-6). Basins P and Q, and R and S are closely spaced and both sets have similar rock type and vegetative cover. Consequently, soil depth measurements and salinity variations were conducted only in Basins A, N, Q, S, T, and U.

Soil and weathered bedrock samples were collected for SMC analysis at the same sites that soil depth measurements were recorded (Chapter 3). The samples were analyzed for SMC by a method very similar to that outlined by Laronne (1977). Laronne observed that many fragments did not disintegrate during his procedure. Therefore, the samples were pulverized and sieved in order to provide silt- and clay-sized particles only.

As expected there is a wide range of SMC within the materials in each basin (Fig. 4-6, Table 4-1). The weathered bedrock samples had a higher average SMC than the soil samples (Table 4-1). However, an analysis of variance shows that, in five of the six basins, there is no significant difference in means of the soil and weathered bedrock samples.

A plot of SMC data (Figure 4-6) and an analysis of variance shows that the six basins may be divided into two sets. Basins A, N, and Q



4-6 Soluble mineral content (SMC) of surficial materials in six badland drainage basins (from Johnson, 1982).

Table 4.1. Summary of SMC analysis for small drainage basins on Mancos Shale (from Johnson, 1982).

Basin	Range (%)	Soil (avg. SMC%)	Weathered bedrock (avg. SMC%)
A	0.74 - 13.81	5.10	6.12
N	0.81 - 18.40	4.82	5.90
Q	0.30 - 17.79	4.76	7.80
S	0.16 - 19.92	3.45	8.56
T	0.23 - 19.22	1.95	5.08
U	0.20 - 19.72	0.28	3.37

generally have higher SMC values than Basins S, T, and U, but the range of SMC is greater in Basins S, T, and U. In five of the six basins, Basin Q being the exception, there is no significant difference between the mean SMC of soil and weathered bedrock.

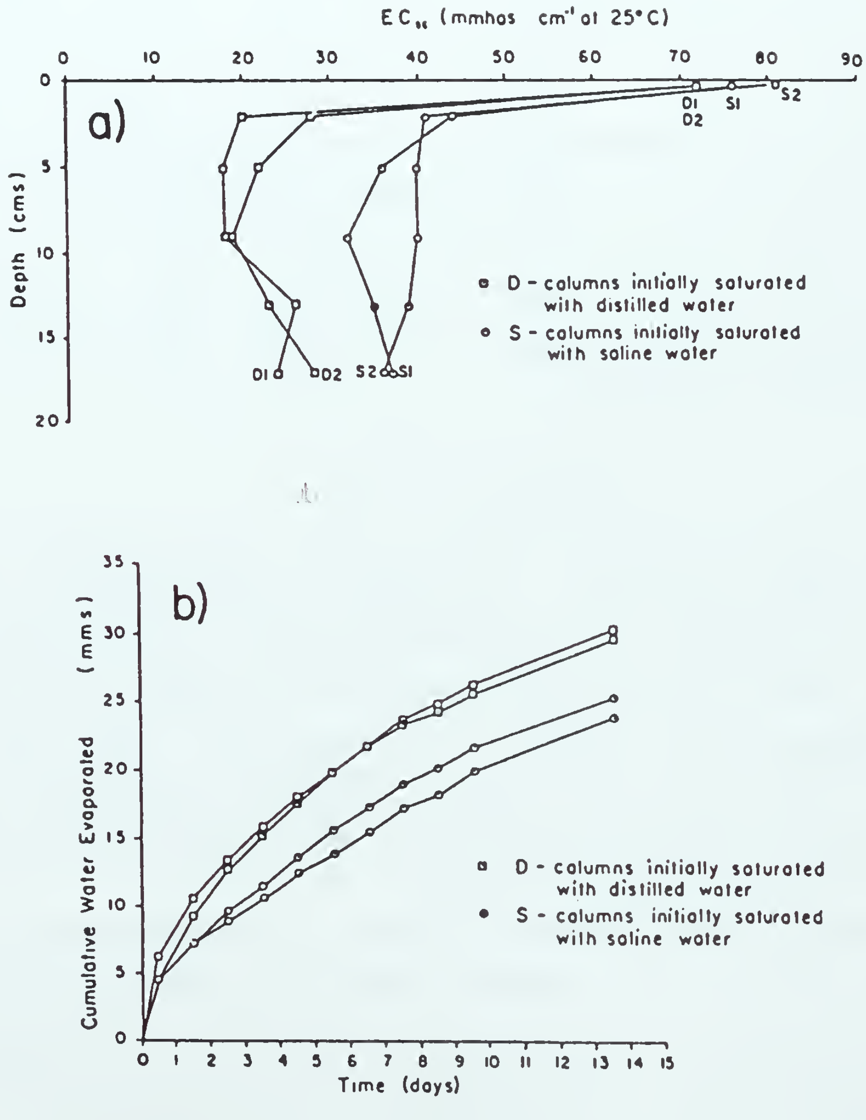
The explanation is based on the lithology of the basins. Basins A, N, and Q are underlain primarily by shale which contains evaporite salts. Basins S, T, and U are underlain primarily by interbedded shale and sandstone. The sandstone lenses contain only calcite as cement (Fisher et al, 1961). Consequently, a unit volume of shale will have a higher SMC than a unit volume of interbedded shale and sandstone. The SMC means for Basins S, T, and U are lower than Basins A, N, and Q because they have different shale to sandstone ratios. Therefore, basins underlain by shale produce more salts than basins underlain by interbedded shale and sandstone.

Variability of SMC

Sediments rich in soluble minerals should develop saline surface crusts under proper conditions. For example, several reaches of North Miller Creek, a tributary of the Price River Basin, are incised into the Mancos Shale. Most of the channel flow does not percolate into the bed, and bed materials dry primarily by evaporation, rather than by infiltration. As a result very saline, efflorescent crusts are formed, and the mean SMC of bed crusts developed in North Miller Creek is 10% as compared with only 1% for the bed proper.

A high concentration of soluble minerals in surface crusts leads to efflorescence (Fig. 4-7a). Bhasker, Bowles and Wagenet (1981) have recently demonstrated that efflorescent crusts form a physical barrier for further evaporation of soil moisture (Fig. 4-7b), and that even slightly soluble minerals are precipitated in the efflorescence.

The surface crusts of the lower and upper Mancos Shale gully walls of North Miller Creek contain 1.07 and 0.76 percent soluble minerals, whereas the SMC of the Mancos Shale beneath the crusts are merely 0.63 and 0.69 percent, respectively. Although the crusts are slightly richer in soluble minerals than the bedrock, the difference is not statistically significant. It is believed that the difference between



4-7 Laboratory generation of efflorescent crusts on Mancos Shale (after Bhasker, Bowles and Wagenet, 1981); (a) increase of EC at surface due to development of efflorescent crust and (b) decrease of evaporation due to development of a salt crust.

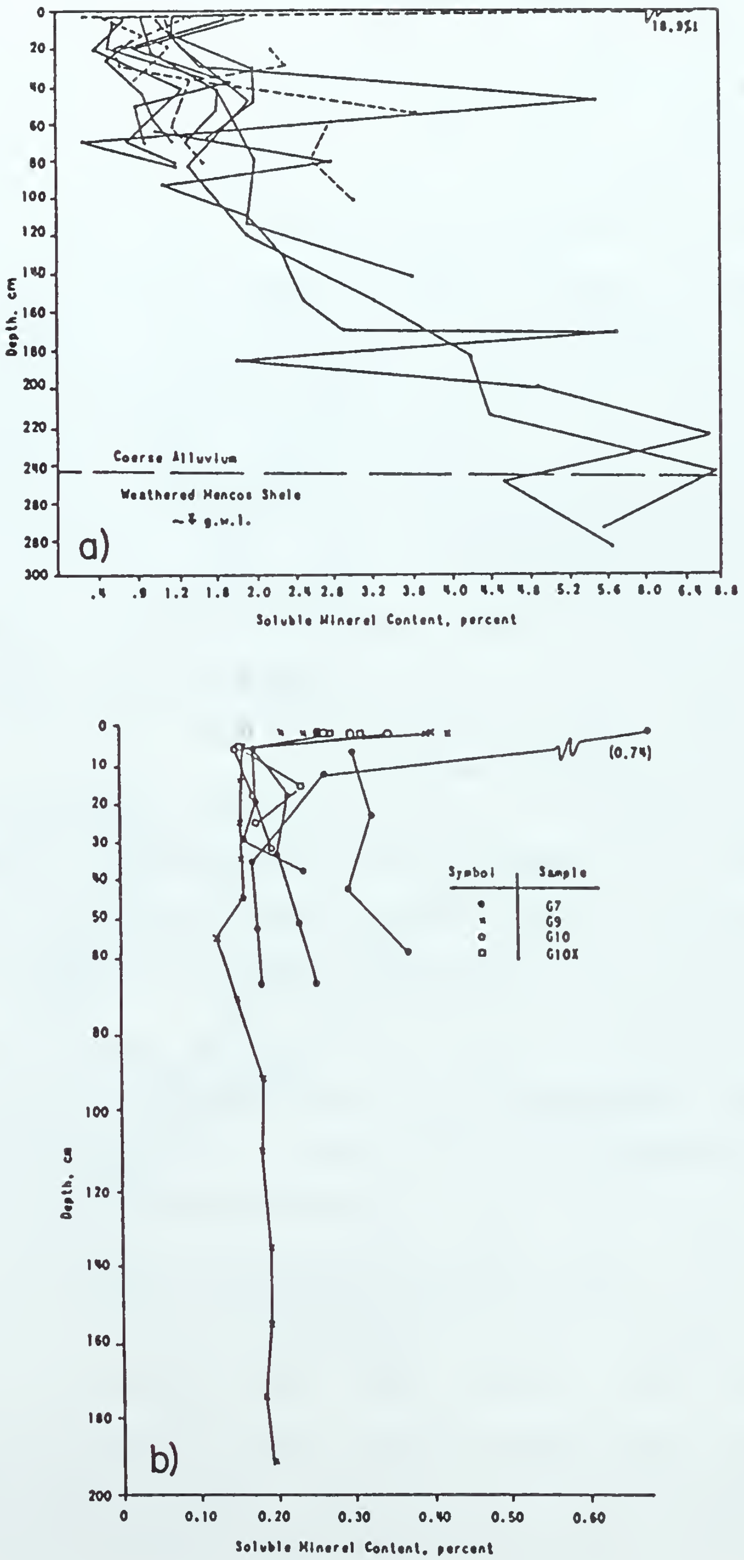
the upper and lower gully walls is due to the low moisture content of the upper wall, which prevents formation of saline crusts. The lower wall comes in contact with water frequently enough that transport of solutes to the outer surface is more pronounced than in the upper wall.

Where permeability is very high, the upper part of the surficial materials, whether crusted or not, will be thoroughly leached. For example, the surface of Mancos Shale hillslopes, may contain one third less soluble minerals than the material underlying them (Shen et al, 1981; Wagenet and Jurinak, 1978). The EC of 14 pairs of Mancos Shale samples (Ponce, 1975) were analyzed, and they also show leaching of the surface crust; the upper-most samples (0-2.5 cm) were on average half as saline as the friable underlying (15-30 cm) material. Leythauser (1973) and Whitmore (1976) also provide data showing that the upper layer of weathered Mancos Shale is leached.

The preceding analysis shows that surface salinity increases as permeability decreases and as the opportunity for wetting and evaporation increases. Much of the salt buildup at the surface appears to originate from the underlying material.

The vertical variation of SMC is not solely restricted to the difference between the surface and underlying materials. Indeed, SMC increases to a maximum of about 6.8% at a depth of between 2.2 and 2.4 m (Fig. 4-8a) just above the contact with saturated and deeply weathered Mancos Shale at 2.5 m in Mesa Creek.

The increase in SMC with depth is not noted in the bed of West Salt Creek (Fig. 4-8b). Although the mean SMC of the crust is higher than that at any other depth, the difference is not significant. An explanation for the constant SMC in these bed materials is the general 'sterility' of West Salt Creek alluvium and its remoteness from contamination by ground water, which was formerly in contact with Mancos Shale. Coarse alluvial terrace deposits also showed no significant trend in SMC with depth (Laronne, 1977). Bed samples from a location where the channel abutts against Mancos Shale and where the alluvial fill of the present channel is very shallow, demonstrate an increase in SMC with depth (Fig. 4-8a). In summary, SMC increases with depth in shallow alluvium overlying Mancos Shale and also in the shale proper



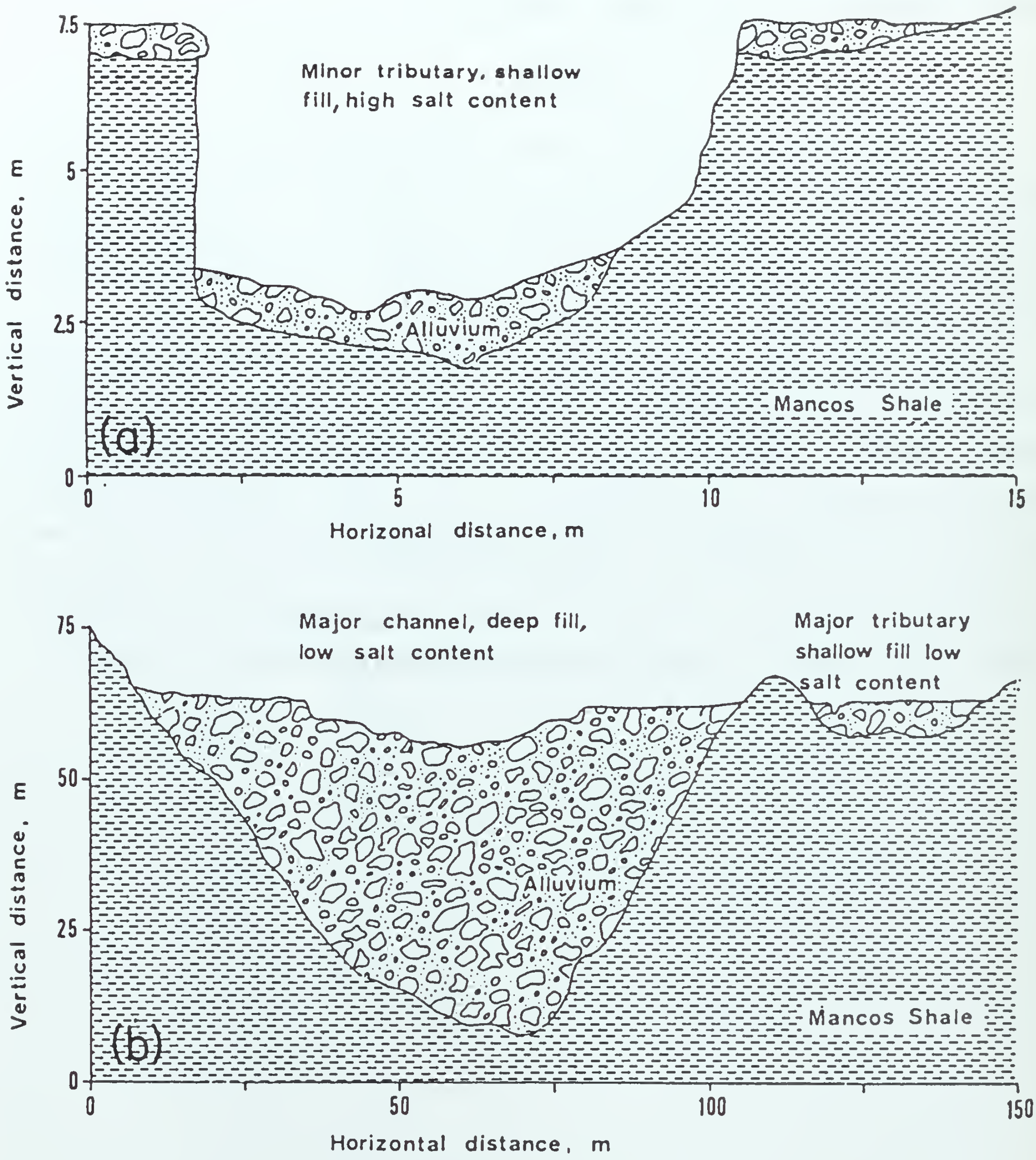
4-8 Vertical variation of SMC of bed materials (a) Mesa Creek (solid lines) and Section G8, West Salt Creek (dashed lines), (b) other west Salt Creek locations (after Laronne, 1977).

(Fig. 4-9a), whereas a uniform SMC with depth characterizes deep and leached bed materials and terrace deposits (Fig. 4-9b).

Summary

The variability of SMC in surficial Mancos Shale and alluvium is high. In addition, the SMC of the various members of the Mancos Shale differs. Even within one stratigraphic unit SMC will be significantly different depending upon the presence or absence of sandstone lenses, which are less saline.

Surface materials can be highly saline where efflorescence has concentrated soluble minerals or low in SMC as a result of leaching. Surface salinity increases as the permeability of the underlying materials decrease. The conclusion to be drawn from the analyses discussed in this chapter is that the variability of land forms and lithology is such that a well planned and carefully designed sampling procedure is required in order to establish the magnitude of diffuse-source salt production from different areas of Mancos Shale terrain.



4-9 Channel cross sections of idealized valley where alluvium overlies Mancos Shale. See text for details.

Chapter 5) HYDROLOGY, SEDIMENT YIELD AND SALINITY

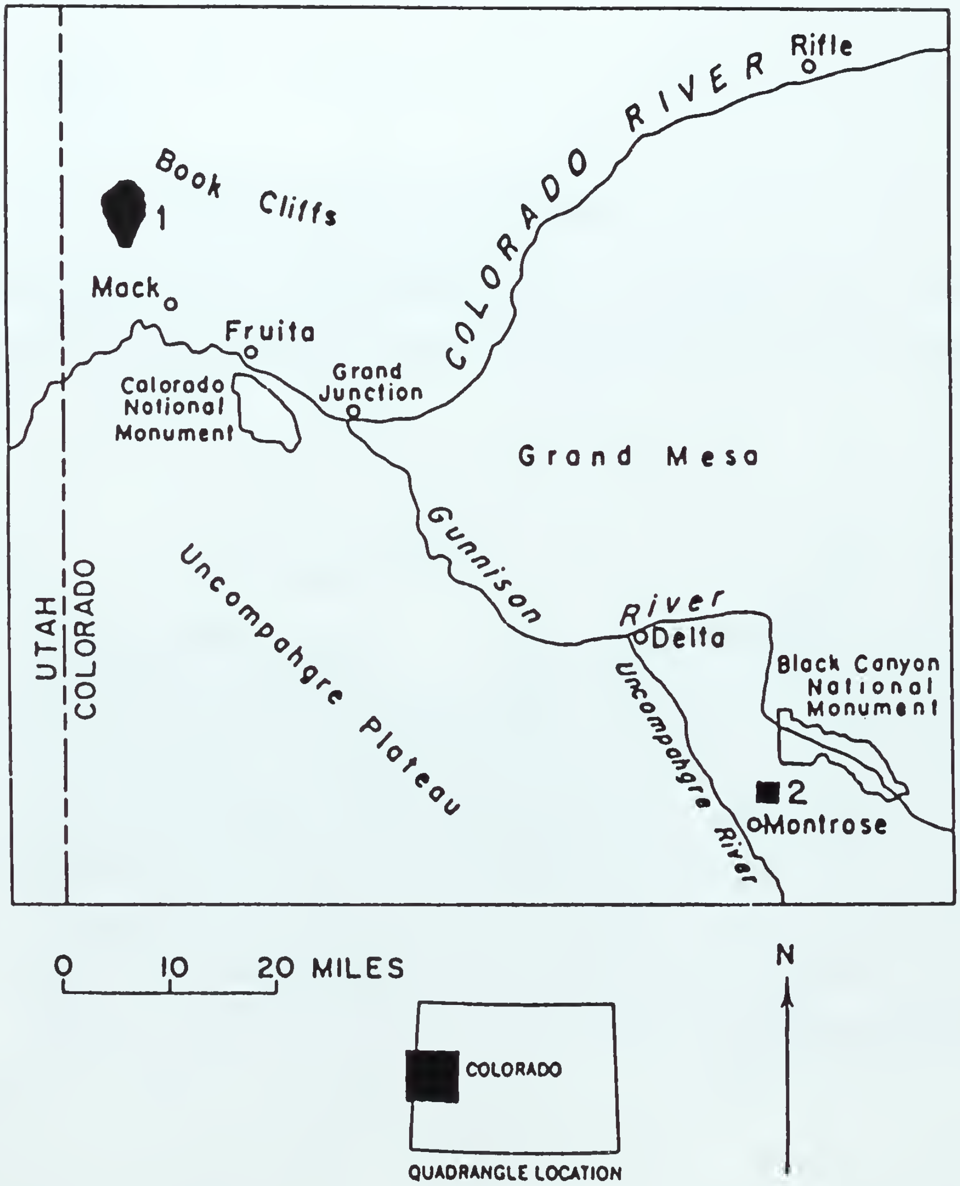
The most productive and longest study of the hydraulic character of Mancos Shale terrain was administered by the U.S. Geological Survey at Badger Wash, Colorado (Fig. 5-1). The results will be discussed in some detail as they provide an understanding of salt and sediment production from an area of active erosion that was classified by Johnson (1982) as badlands.

Badger Wash

The Badger Wash research area was selected by a team representing the Geological Survey, Forest Service, Bureau of Land Management, Bureau of Reclamation, and Fish and Wildlife Service for a twenty-year study that began in 1953. The objectives of the study were to compare runoff and sediment yield from grazed and ungrazed watersheds and, in addition, to develop a better understanding of the hydrologic character of Mancos Shale terrain. Badger Wash, therefore, is an area in which considerable information on meteorology, runoff, sediment yield, and the geomorphology of the drainage basins is available. Unfortunately, during the period of study from 1953 to 1973 no attention was paid to the chemical quality of the water flowing from the slopes and in the channels at Badger Wash. Nevertheless, the wealth of information available for this area and the insight it provides into the hydrologic characteristics and the erosional and depositional features of the Mancos Shale terrain is significant for an understanding of the diffuse-source salinity problem.

Badger Wash drainage basin is located in western Colorado only a few miles east of the Utah-Colorado boundary and about twenty-five miles west of Grand Junction, Colorado (Fig.5-1). Badger Wash is a tributary to West Salt Wash, which in turn is tributary to the Colorado River. The area of the basin is essentially 6.5 square miles, and it lies at an elevation of approximately 5,000 feet above sea level.

The hydrologic data, that was obtained during the Badger Wash study, was collected in small reservoirs that provided traps for runoff and sediment yield. Of the twenty-two small drainage basins that contained



5-1 Index map showing locations of two study areas. Numbers on map designate study areas as follows: (1) Badger Wash area, (2) Montrose area (from Schumm and Lusby, 1963).

reservoirs, eight were selected for intensive study. In order to determine the effect of grazing exclusion on runoff, sediment production, vegetation and infiltration, four adjoining pairs of watersheds were selected. One watershed of each pair was fenced to exclude grazing and the other was subjected to normal grazing use.

In June 1958 a study of hillslope erosion was begun (Schumm and Lusby, 1963; Schumm, 1964) in order to obtain information on rates of hillslope erosion. In addition, a geomorphic analysis of 7 drainage basins was made in order to relate the hydrologic and geomorphic characteristics of small Mancos-Shale drainage basins. Similar hillslope studies were carried out near Montrose, Colorado. The hillslope-erosion study was terminated in April 1962, but measurements of soil creep were continued for 7 years. The results of the slope study are relevant to an understanding of runoff and sediment yield, and therefore, to salt production.

Climate

The climate of the study areas fluctuates between arid and semiarid. According to Thornthwaite (1941) the climate is arid from 26 to 50 percent of the time. Average annual precipitation at Fruita, 16 miles southeast of Badger Wash, is 8.3 inches. Average annual precipitation for the Montrose (No. 2) weather station is 9.1 inches. The climate is of the continental type with wide annual and daily variations in temperature. For example, the maximum temperatures for the Fruita and Montrose stations in 1960 were 103° F and 100° F respectively, and the minimum temperature for both was -8° F (U.S. Weather Bureau, 1958-61).

Total precipitation for each period between erosion measurements is given on Table 5-1 for Badger Wash, Montrose (No. 2) and Fruita. The Fruita data are included because they provide information on the amount of snowfall near Badger Wash. Total precipitation at Badger Wash and Montrose for the period of study is similar, but about 25% less was measured at Fruita. However, total snowfall at Fruita is about half that measured at the Montrose stations, and this difference in snowfall is the only important climatic difference between study areas.

Table 5.1. Total precipation and snowfall for each period between erosion measurements for Badger Wash, Montrose (No. 2) and Fruita weather stations. Data from U.S. Weather Bureau 1958-61, (from Schumm, 1964).

Period	Dates	Montrose No. 2		Badger Wash	Fruita	
		Total precipitation (inches)	Snowfall (inches)	Total precipitation (inches)	Total precipitation (inches)	Snowfall (inches)
1	June 1-Sept. 28, 1958	1.21[1]		1.76	2.00	5.8[3]
2	Sept. 29, 1958-May 25, 1959	3.67	10.1	2.71	2.76	
3	May 26-July 28, 1959	0.54		.35	0.24	
4	July 29, 1959-April 20 1960	10.95	44.2	6.90	7.19	24.5
5	April 21-Nov. 17, 1960	3.04		3.96	2.10	
6	Nov. 18, 1960-Mar. 25, 1961	3.43	26.8	2.15	1.50	2.0
7	Mar. 26-Sept. 7, 1961	5.17	5.5	4.13	3.16	
8	Sept. 8, 1961-April 17, 1962	5.38	9.3	8.97	6.16	15.8
	Total precipitation	33.37	95.9	30.93	25.11	48.1

[1]Profiles at Montrose installed June 26, 1958. Precipitation at Montrose for period June 26 - Sept. 28, 1958.

[2]Average obtained from 10 recording rain gages (Lusby et al, 1971).

[3]No record of snowfall for February 1959. Amount estimated on basis of precipitation occurring on days when temperature fell below 31°.

Vegetation

Vegetational cover is sparse and on some of the steep south and west-facing slopes in the Montrose area vegetation is absent (Fig. 5-2a). At Badger Wash (Fig. 5-2b) the crowns of living perennial plants cover only 8 to 15 percent of the ground surface (Lusby et al, 1971).

Vegetation is of the typical desert-shrub type; shadscale, Gardner saltbush and galleta grass are the dominant types. During wet years the plant density is increased slightly by growth of annual plants.

Studies of the effect of plant cover on runoff and sediment yield by Branson and Owen (1970) show that, as might be expected, the greater the percentage of bare ground the greater will be the annual runoff (Fig. 5-3).

Land Use

In Badger Wash both cattle and sheep are allowed to graze from November to May 15. Cattle are fed at the lower end of the basin, and most of the trailing on the hillslopes in the southern half of the area is caused by cattle. Trailing in the northern half of the area is caused by sheep. Four small drainage basins in the Badger Wash area were fenced to exclude grazing animals. No grazing animals were observed in the Montrose area, and there was no tracking on these steep slopes during the period of study.

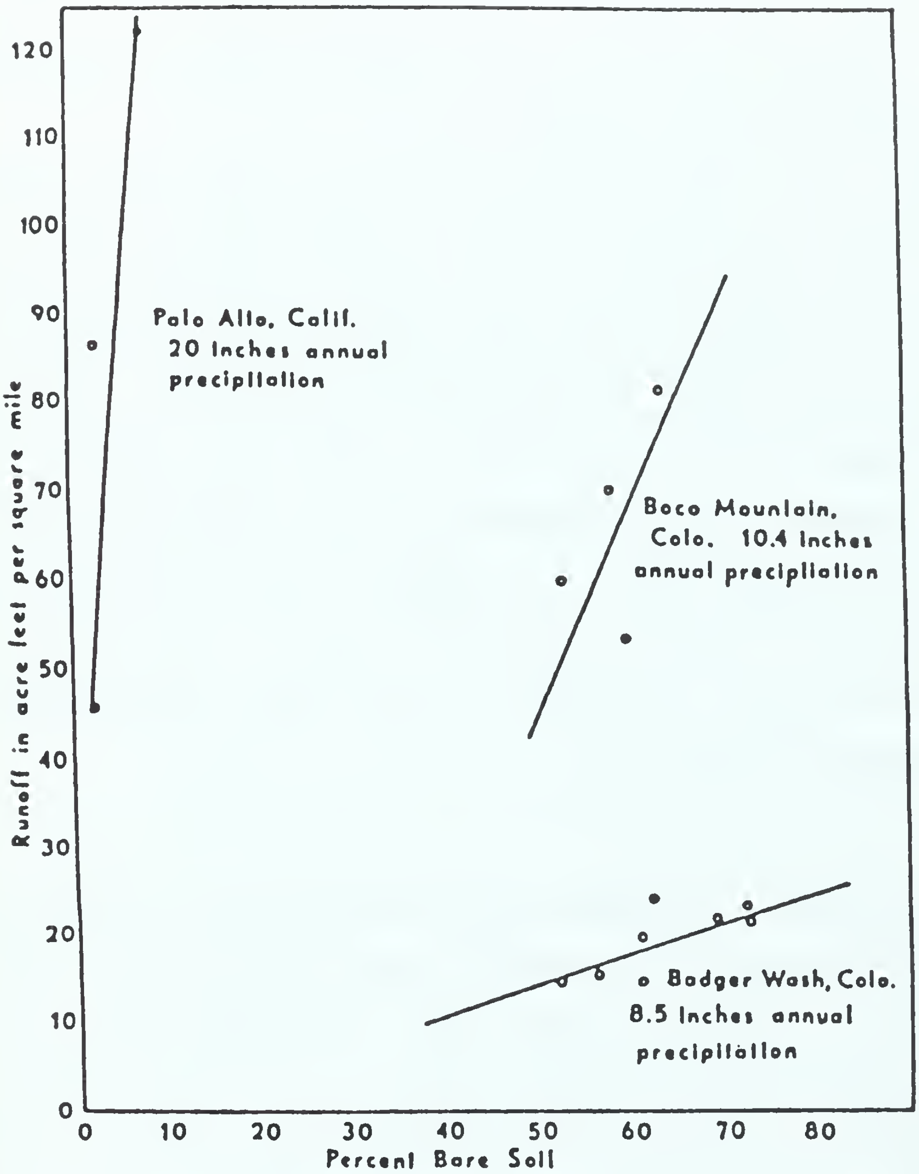
Geology and Soils

At Badger Wash veinlets of gypsum and calcite are common in the Mancos Shale and thin sandstone beds up to 0.5 foot thick are present. The Mancos Shale exposed in the Montrose area is similar except that less sandstone is present. Thin platy fragments of sandstone and gypsum occur on most slopes. On the hillslopes a zone of platy shale fragments up to about 5 inches thick lies directly on the bedrock. Above this zone of weathered shale fragments lies the surface material, which appears either as a mass of loose soil aggregates or a crust about 2 inches thick.

The soils in the study are of the Persayo, and Billings soil series (Knobel et al, 1955; Nelson and Kolbe, 1912). Clay identified in the

5-2a View toward head of main drainage system in Montrose area. Contrast steep, almost-bare slopes with those of Fig. 5.2b (from Schumm, 1964).

5-2b View to west down Windy Point drainage basin toward Badger Wash. Fence encloses Windy Point Drainage Basin (from Schumm, 1964).



5-3 Relation between percentage of bare soil and runoff for watersheds in three different precipitation zones (from Branson and Owen, 1970).

Billings soils is primarily illite with very little montmorillonite (Knobel et al, 1955, p. 92). Illite, chlorite, and mica were identified by X-ray analyses in the soils from both Montrose and Badger Wash. In addition, vermiculite is present in the Montrose soil. Bedrock samples taken near Montrose have four times the total cation content (Ca, Mg, Na) of the bedrock sampled in Badger Wash.

Swelling of the soils was determined in two ways, by a shrinkage test and a free swell test. Both methods probably gave a maximum value for swell which seldom occurs in the field. The free swell test showed a 20% increase in volume of the Badger Wash surface material, and a 25% increase in volume of the platy material and the bedrock. The surface material sampled at Montrose increased in volume 25%, the platy material 30% and bedrock 58%. Alluvium sampled at Badger Wash showed only a 5% swell. The average swell of Badger Wash soils, as indicated by shrinkage tests on 7 samples, is 33%. The average swell of Montrose soils, as indicated by shrinkage tests on 10 samples is 43%. The tests reveal appreciable swell of soils in both areas. Montrose soils, however, show greater volume changes due probably to their higher sodium content and to the presence of vermiculite.

Landforms

The topography of the Badger Wash and Montrose study areas has been formed by the dissection of pediments lying near the base of the Book Cliffs and at the base of Black Mesa. The Badger Wash area was classified as badlands by Johnson (1982). The areas are desolate in appearance, and the poorly-vegetated, gray-colored, rounded, shale hills lend a monotonous character to the landscape (Fig. 5-2a,b). Drainage density, as measured on very detailed topographic maps, for some of the small fifth-order drainage basins at Badger Wash is about 100. This is a high value indicating a fine-textured topography.

Hillslope Erosion

Methods of Investigation

In order to measure hillslope erosion, profiles were established on 21 Mancos Shale hillslopes in June 1958. Each profile extended from the crest of the slope directly down to the adjacent stream channel or in some cases across a flat alluvial or erosional basal slope toward the nearest channel. Along each profile metal stakes, 18 inches long, were driven into the slopes normal to the surface. The stakes were installed to allow measurement of hillslope erosion by their progressive exposure and to afford stationary reference points to which the position of various types of markers could be related. Markers were placed along the profile lines on the slopes to indicate by their changing position the effects of creep, the slow downslope movement of soil by gravity. The profiles were visited semiannually, in the spring and the fall of the year, when stake exposure and position of the markers were measured.

Field Observations

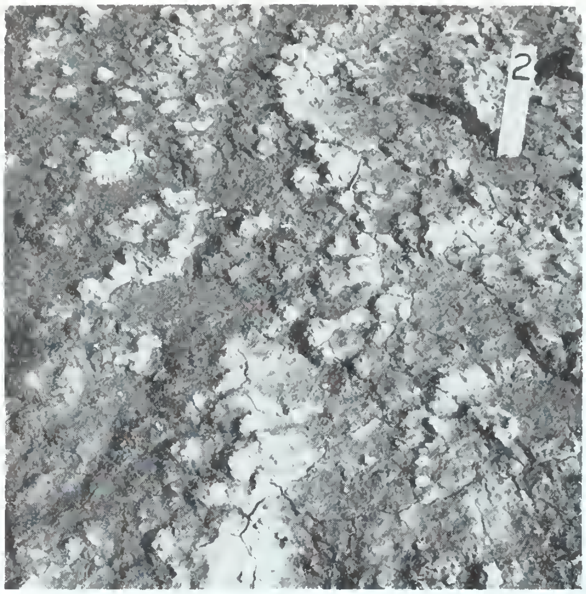
Previous observations and measurements of erosional phenomena (Schumm, 1956a, 1956b) indicate that swelling soils are highly permeable and that these soils creep when wetted. It was assumed that rates of erosion and runoff from hillslopes comprised of such material would be low. Casual observations during summer thunderstorms in the study areas seemed to support these preconceptions. Nevertheless, early in the study it became apparent that the situation was not as simple as first supposed. Residents in the Montrose area stated that at certain times the slopes yielded high rates of runoff. During the semiannual visits to the study areas, it was not necessary to measure stake exposure and marker movement to explain these statements, for it became obvious that seasonal changes in soil characteristics were great enough to significantly affect the erosional and hydrologic character of the slopes.

The study areas were visited many times but never during mid-winter. Nevertheless, the observations made during the semiannual visits can be summarized for a typical year. For convenience this discussion begins with the events immediately following a summer storm. The hillslopes are wet; they retain a characteristically lumpy appearance, and dessication fractures form as the soil dries (Fig. 5-4). Upon complete drying, the surface is composed of a network of fine fractures (Fig. 5-5). The slopes, sealed except for the network of fractures which close as the soil is wetted, are relatively impermeable. Under this condition of low permeability, slopewash and rilling are effective geomorphic agents. With additional precipitation rills become prominent on the hillslopes (Fig. 5-6). If the predominant erosive process on the Mancos Shale hillslopes is sheetwash or surficial runoff, then the rills should continue to develop, and perhaps enlarge to form permanent channels. However, with the coming of winter and freezing temperatures, a transformation occurs.

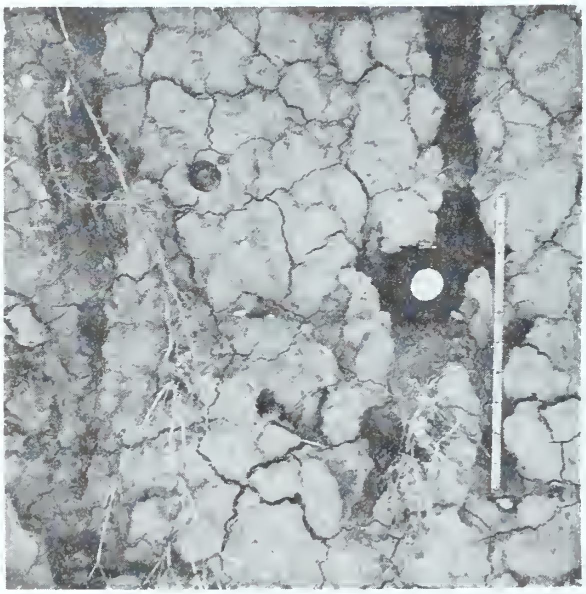
Heaving and loosening of the soil by frost action during winter destroys the rill channels formed during the summer (Fig. 5-7). Freezing temperatures alone are not enough, however, for moisture is also required for frost heaving. Snow plays an important role in the destruction of the relatively impermeable surface formed during the summer. Snowfall is gentle and does not further compact or seal the surface, and melting of the snow wets the soil and permits frost action.

Granular ice crystals were observed in the upper soil zone during the winter. The crystals serve as growth centers, and water is drawn to them from surrounding particles. This growth of ice crystals in soil pores and the simultaneous drying of adjacent soil causes cracking and loosening of the dry soil (Baver, 1956, p. 153). The areas between dessication fractures are further reduced in size, and the entire soil surface is raised and loosened by the growth of granular ice crystals in the voids. Several periods of such freeze and thaw activity cause a transformation of the partially sealed surface (Fig. 5-5) to a highly permeable surface composed of soil aggregates (Fig. 5-8).

In spring following the last severe frost, the slope surfaces are unstable. Tracking by animals at this time of the year can cause important downslope movement of soil (Fig. 5-7). Spring rains shortly change this situation by compacting the loose surface by rainbeat. The



5-4 Mancos Shale slope surface in summer (August, 1959). Surface has been sealed by rain and incipient dessication fractures are present (from Schumm, 1964).



5-5 Mancos Shale slope surface in fall (Sept. 1958). Surface has been sealed and rill channels are present. Infiltration takes place primarily through dessication fractures (compare with Fig. 5-8) (from Schumm and Lusby, 1963).

5-6 Hillslope in Twins Drainage Basin, Badger Wash in autumn (August, 1959) showing rilled surface produced by summer rains (from Schumm and Lusby, 1963).

5-7 Hillslope in Twins Drainage Basin, Badger Wash in spring (March 1961) showing unrilled surface with some tracking (from Schumm and Lusby, 1963).

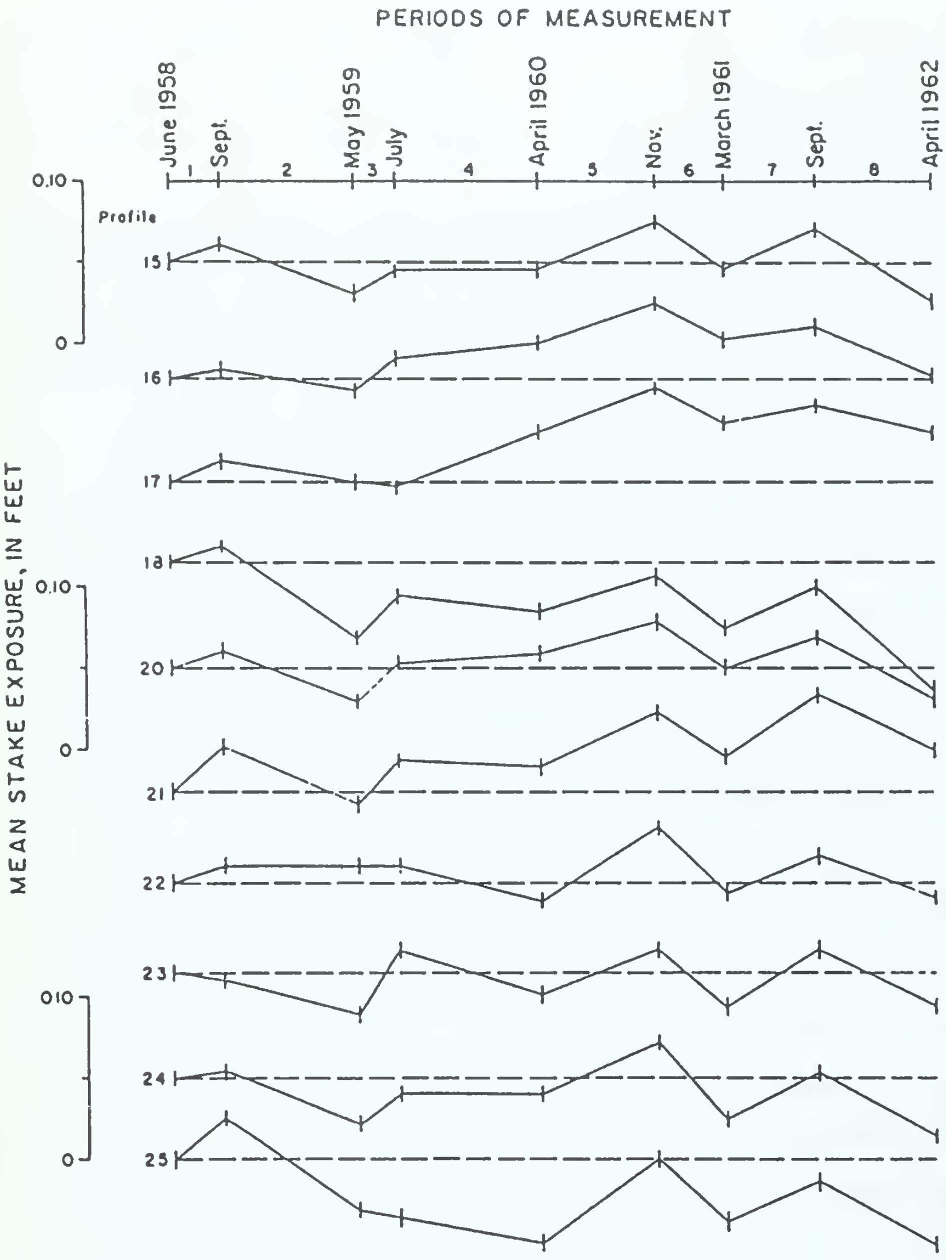
5-8 Mancos Shale soil surface in spring (March 1961). Surface is very loose and rill channels are almost obliterated. Compare with Figure 5-4 (from Schumm and Lusby, 1963).

aggregates tend to be destroyed, as their edges sluff into the cracks and partly close them. A crust forms over the outer surface of the aggregates, and, although reduced in height, they become more stable. Even after the surface is sealed by rains, the aggregates formed during the winter may be recognized as irregularities on the ground surface (Fig. 5-3). With continued rainfall, runoff again becomes important, and the obliterated rill channels are scoured and become prominent. With the reappearance of the rills the annual cycle on the Mancos-Shale hillslopes is completed. An annual cycle of rill formation and obliteration is a criterion of important annual changes in the erosive process operative on hillslopes (Schumm, 1956a).

Measurements of Erosion

Although the majority of markers and stakes showed similar changes during any one period, it is true that all did not conform. For example, the rapid downslope movement of a marker during one period may cease if it lodges against vegetation or reaches another position of relative stability. Nevertheless, the average movement of markers and stake exposure for a given period indicate clearly the progress of erosion on these hillslopes.

Exposure of Stakes: When stakes are used to measure erosion, it is the progressive exposure of the stakes that reveals the rate at which the surface is being lowered. The Badger Wash and Montrose data will be considered separately because of the differences in swelling characteristics and snowfall measured during the study. The Montrose profiles will be discussed first, for they were subjected to the most active erosion. In Figure 5-9 the mean exposure of stakes on the Montrose profiles is plotted against date of measurement to illustrate changes in stake exposure with time during the study. The June 1958 measurements give the average initial exposure of stakes on installation, and they are plotted as zero exposure on the dashed line in each case. The subsequent measurements show change in exposure with time. The September 1958 measurement showed an increase of exposure on all profiles except number 23 which showed a slight decrease in exposure. These measurements indicate that an average of .012 foot of



5-9 Mean stake exposure at Montrose for each measurement period. Average stake exposure is plotted against measurement period to illustrate seasonal changes of stake exposure. The first measurements made in June 1958 are plotted as if exposure were zero to simplify plotting of the data (from Schumm, 1964).

erosion occurred between June and September 1958 under the influence of 1.21 inches of precipitation (Table 5-1).

The graphs of Fig. 5-9 show that mean stake exposure follows essentially the same pattern for all profiles, and, therefore, the discussion may be followed on Fig. 5-10 where mean stake exposure is plotted for all 10 Montrose profiles.

If erosion on the slopes were to continue at a rate approaching that of period 1 then the average plot of stake exposure should ascend to the right as erosion progressively exposes the stakes. However, this is not the case, for when stake exposure was measured in May 1959, most stakes were found to be exposed less than in September 1958. This reduction in the exposure of the stakes is not an isolated event at Montrose. The stakes are exposed by erosion during the summer months (periods 1, 3, 5, 7), but they are buried during the winter months (periods 2, 4, 6, 8).

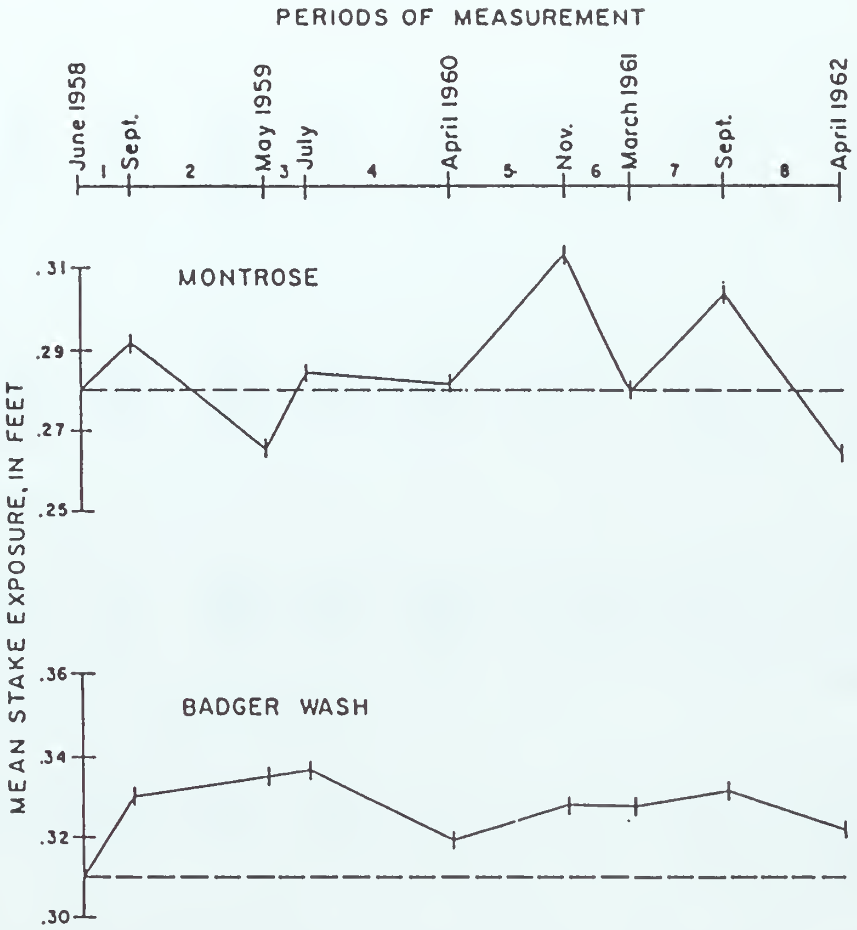
The Badger Wash hillslope profiles (Fig. 5-11) do not show the seasonal changes of stake exposure as clearly as those at Montrose. Indeed, changes of average stake exposure were minor during periods 2 and 3 and periods 6 and 7 (Fig. 5-10). Nevertheless, most of the stake profiles show changes similar to those recorded at Montrose for at least portions of the period of record.

The greater changes in stake exposure at Montrose (Fig. 5-10) can be explained partly by the greater swelling of the Montrose soils. However, the amount of snowfall during the winter periods of measurement is also of prime importance. For example, during period 2 (Sept. 28, 1958 to May 25, 1959) average stake exposure decreased .027 foot at Montrose and exposure increased .005 foot at Badger Wash. During this period 2.71 inches of precipitation fell at Badger Wash, and 5.8 inches of snow fell at Fruita. At Montrose, precipitation was greater, 3.67 inches, including 10.1 inches of snow (Table 5-1). As suggested previously, the amount of snowfall is probably indicative of frost effects in the soil. Thus, the greater heaving of the soil and stake burial occurred at Montrose during period 2.

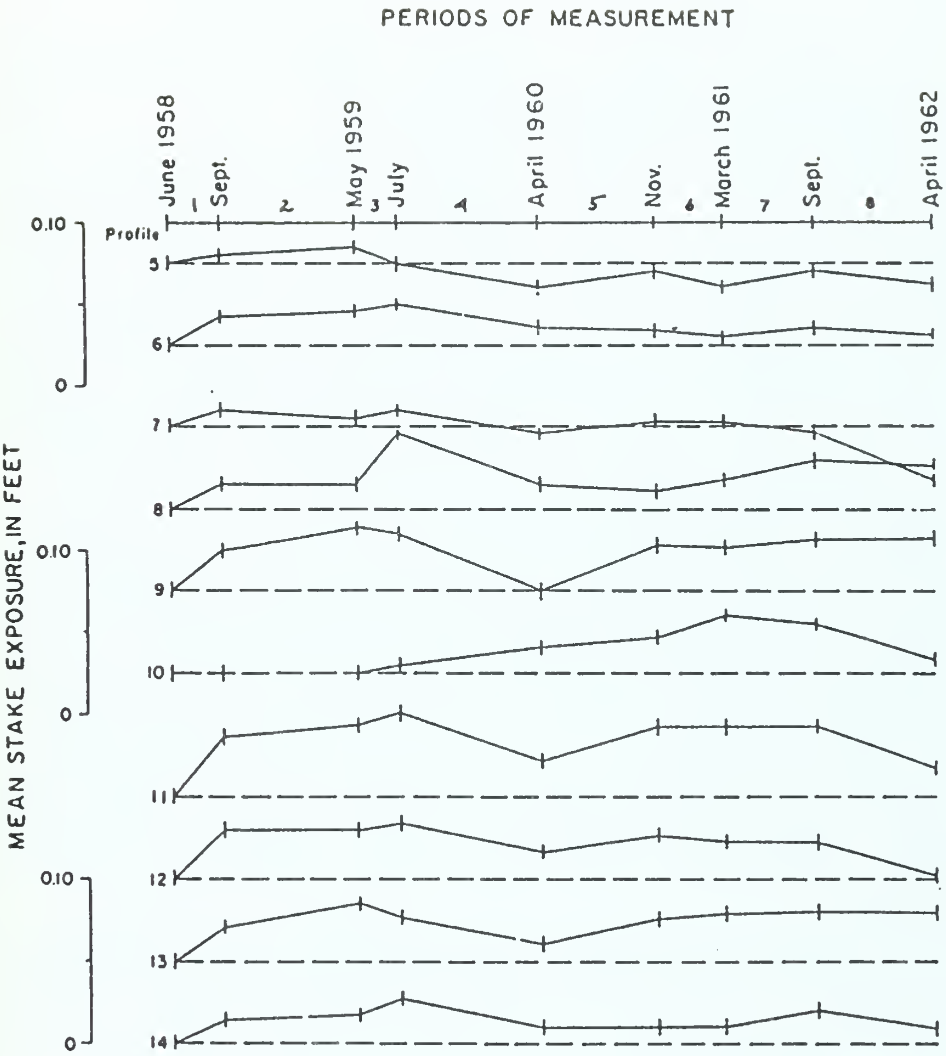
However, a different relationship is shown for period 4 (Fig. 5-10, Table 5-1) for other reasons. Period 3 shows a reduction of exposure by swelling and heaving of the surface at Badger Wash, but this tendency is

Table 5.2. Spring and fall Precipitation and runoff at Badger Wash, 1954-1961, (from Schumm and Lusby, 1963).

Range of Storm Precipitation, inches	Period	Number of Storms	Average Precipitation per Storm inches	Average Runoff per Storm inches	Runoff-Precipitation Ratio
0.10 to 0.20	Apr.-June	13	0.15	0.001	0.007
	Aug.-Oct.	23	0.15	0.008	0.050
0.21 to 0.30	Apr.-June	4	0.26	0	0
	Aug.-Oct.	11	0.27	0.039	0.145
0.31 to 0.40	Apr.-June	3	0.32	0.007	0.022
	Aug.-Oct.	11	0.34	0.063	0.185
0.41 to 0.50	Apr.-June	3	0.47	0.020	0.043
	Aug.-Oct.	7	0.47	0.093	0.198
0.51 to 0.60	Apr.-June	1	0.58	0.120	0.207
	Aug.-Oct.	2	0.56	0.180	0.322
0.61 to 0.70	Apr.-June	1	0.69	0.004	0.006
	Aug.-Oct.	4	0.66	0.290	0.440
0.91 to 1.0	Apr.-June	0			
	Aug.-Oct.	2	0.94	0.380	0.400
1.31 to 1.40	Apr.-June	0			
	Aug.-Oct.	1	1.34	0.470	0.350
All storms 0.10 to 1.40	Apr.-June	25	0.26	0.004	0.015
	Aug.-Oct.	61	0.34	0.079	0.232



5-10 Mean stake exposure for ten Montrose and ten Badger Wash profiles (from Schumm and Lusby, 1963).



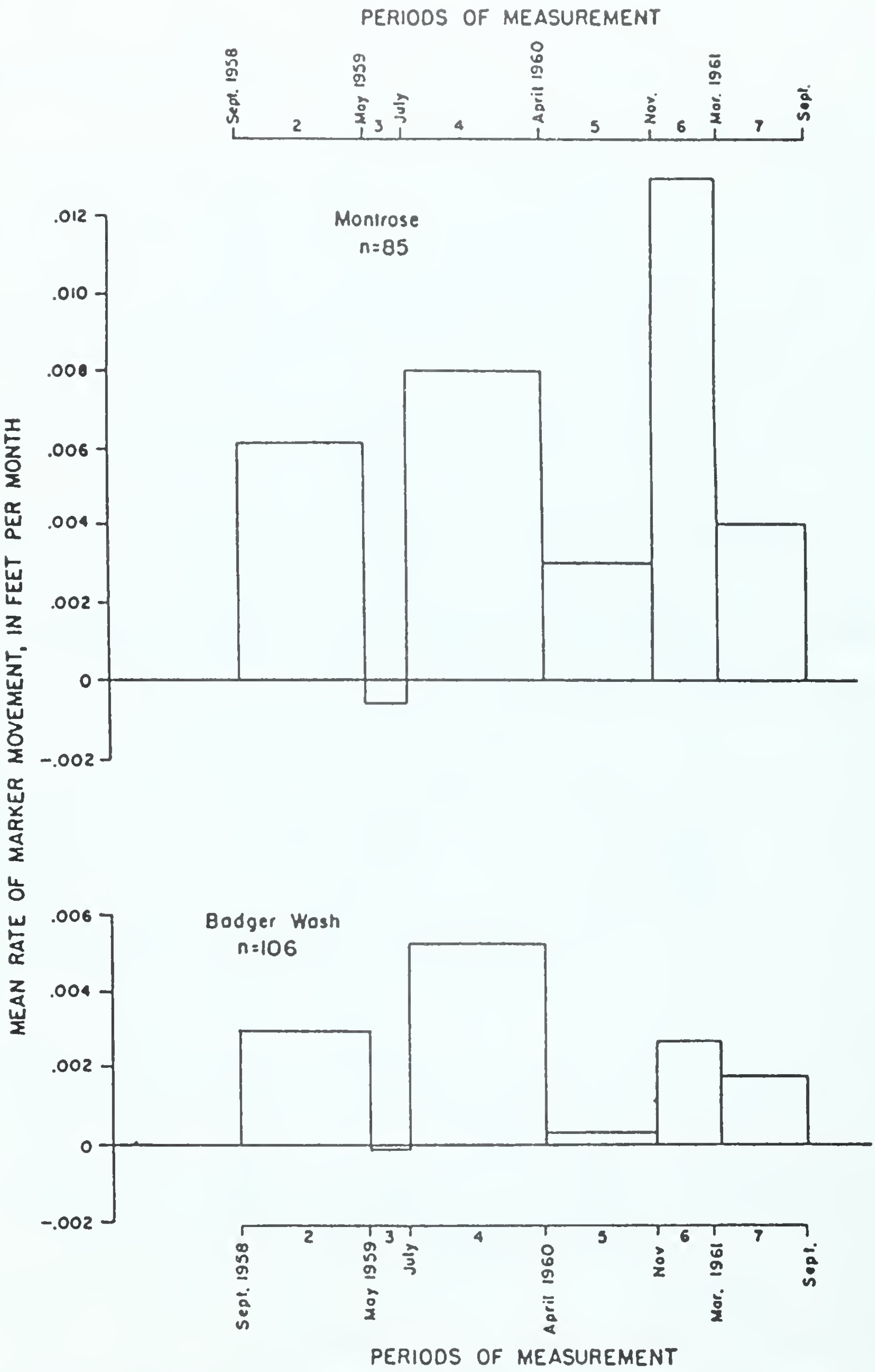
5-11 Mean stake exposure at Badger Wash for each measurement period. Plot is similar to that for Montrose data shown in Figure 5-9 (from Schumm, 1964).

poorly shown at Montrose. This is in spite of greater precipitation at Montrose and much greater snowfall (Table 5-1). This apparent anomaly can be explained only as a result of making the second annual measurements in July instead of in September or October. If the measurements had been delayed until the end of October, 5.26 additional inches of rainfall would have fallen at Montrose. This is a large amount for a 3-month period, and the resulting average compaction of the surface might have been on the order of .015 foot. The following period of heavy snowfall would have caused loosening of the surface, and the typical small stake exposure in the spring would have been measured. By taking the fall measurements in July, the seasonal changes have been obscured, for period 4 is one of considerable compaction by rain and loosening by frost action, each process nullifying the other as far as the plot of Fig. 5-10 is concerned.

Finally the very slight changes in stake exposure during measurement periods 6 and 7 at Badger Wash may be attributed almost entirely to the very small amount of snowfall at Badger Wash during period 6. On the other hand, during period 8 a decrease in stake exposure was recorded at almost every profile (Figs. 5-9 and 5-11). The change was greater at Montrose in spite of the larger amount of precipitation at Badger Wash. This difference undoubtedly reflects the less responsive nature of Badger Wash soils.

The plots of mean stake exposure (Figs. 5-9 and 5-11) show that no progressive exposure of the stakes occurred during the study. Only six profiles, 8, 9, 11, 13 (Fig. 5-11), 17 and 21 (Fig. 5-9), showed a significant net increase in mean stake exposure during four years.

Movement of Markers: The movement of markers during 6 measurement periods was such that seasonal changes in the rate of movement are also apparent (Fig. 5-12). At both Badger Wash and Montrose, marker movement was greatest during the winter, and marker movement was least during the summer. Indeed, during period 3 (May - July 1959) a slight negative movement was recorded both at Badger Wash and Montrose. Although the negative movement is less than the measurement error and can be disregarded, it can be explained partly by the fact that during this short period of record only compaction of the loosened surface occurred.



5-12 Average rate of marker movement during measurement periods (from Schumm and Lusby, 1963).

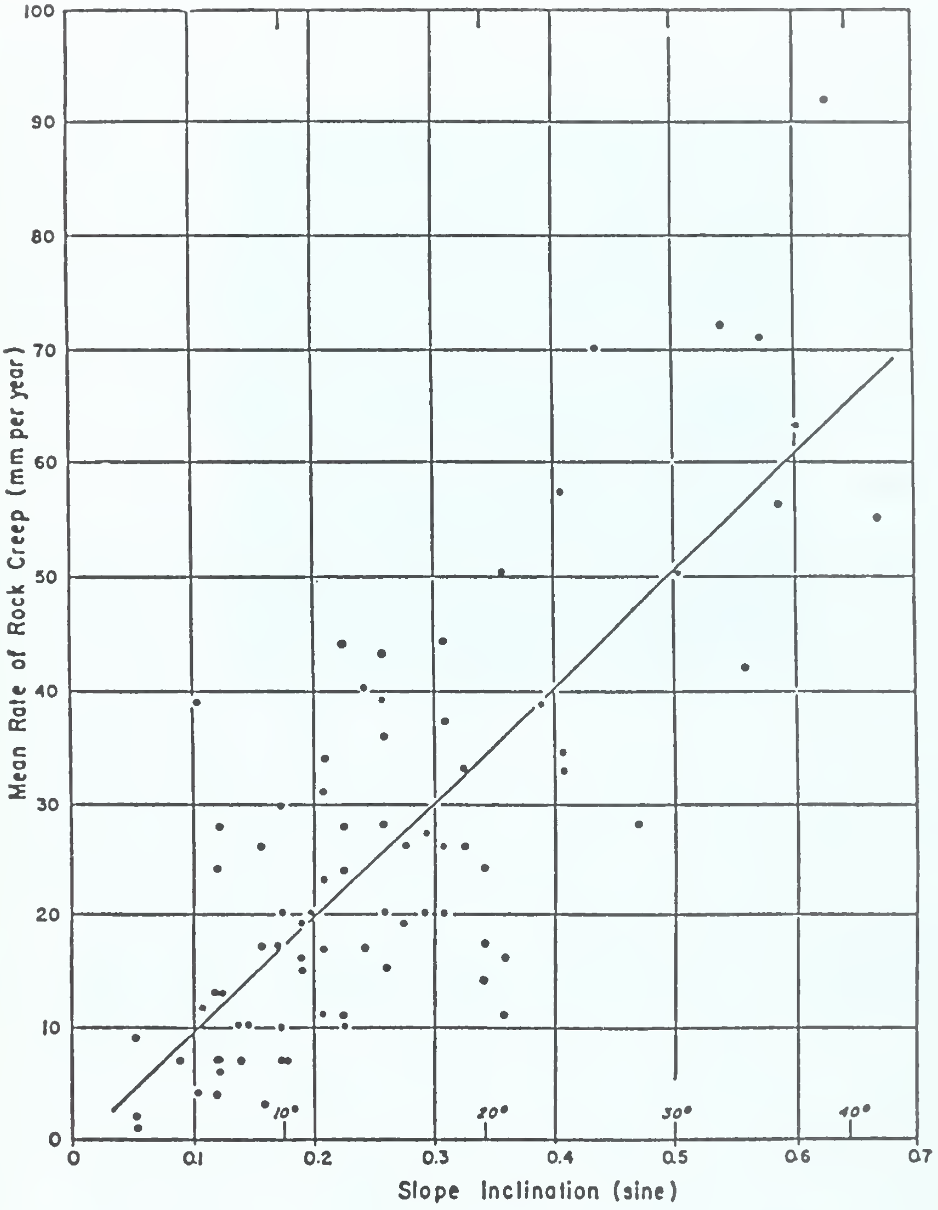
Both sets of data show the same seasonal fluctuations, but the changes are of a greater magnitude at Montrose. Some of this disparity is probably due to the differences in soil materials, for on some of the more sandy areas in Badger Wash very little movement occurred. The remainder of the difference is due to the greater precipitation and snowfall at Montrose as discussed previously.

The movement of individual markers showed great variability (Fig. 5-13). Some markers, even on the steeper slopes, moved relatively little, for their movement was retarded by vegetation. Nevertheless, when marker movement is averaged for a seven-year period of study on the basis of ten percent increments of slope inclination, it is found to be an exponential function of slope inclination (Fig. 5-13). The rates of creep measured on the Mancos Shale hillslopes are surprisingly high for hillslopes in a region of semiarid climate.

The study was not designed to demonstrate the effects of land use or slope aspect on the movement of markers; nevertheless, the data show that movement of markers in unfenced areas at Badger Wash is 3 times that in fenced areas as follows:

Type of Profile	Average Slope (percent)	Total Number of Markers	Total Movement of Markers (feet)
Fenced	35	88	0.11
Unfenced	40	13	0.31

This greater movement of markers in unfenced areas at Badger Wash can be explained only by the trailing of livestock. Trampling tends to compact the surface of the slopes with the usual downslope component of movement accompanying compaction. In general, the rate of movement on unprotected slopes is high because a few markers have been moved several feet as a result of trampling. The remainder of the markers on a given profile may not show movement in excess of that in fenced areas. Therefore, movement greater than normal is not occurring over the entire unfenced profile but only where tracked by livestock.



5-13 Relation between the sine of slope inclination and the rate of movement of rock fragments on Mancos Shale hillslopes. Average rates of rock movement for 0.10 increments of sine are shown as stars (from Schumm, 1967).

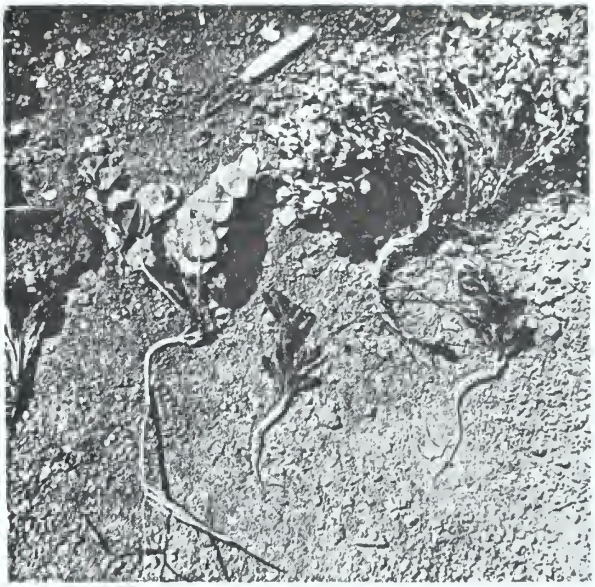
Annual plants show effects of early spring movement and most roots have elbows near the ground surface (Fig. 5-14). The elbows occur near the surface, indicating that only the upper part of the soil is moving downslope.

At several locations holes were augered into the slopes in June 1958. The holes were filled with glass beads, and they were not disturbed until excavated in September 1961. In each of three such locations only the beads in the upper two inches of the hole showed movement downslope. The column of beads was truncated at about 2 inches below the surface, and the beads initially in the upper part of the hole could be traced as far as 2 feet downslope. These observations are confirmation that only the upper soil zone, that overlies the zone of platy shale fragments, takes part in the downslope movement.

Hillslope Segments

In the preceding discussion of process it was noted that a net exposure of the stakes by erosion did not occur during the study (Fig. 5-10). It was concluded that if such erosion did occur it was of small magnitude and was obscured by seasonal changes on the slopes. Nevertheless, the markers showed a progressive downslope movement, and an increase of rate of movement on the steeper slopes (Fig. 5-13). If soil is moving downslope at a faster rate on the steeper portions of the slope then erosion or a loss of material must be occurring at certain points or segments of the profiles.

Studies elsewhere on similar materials (Schumm, 1956a) reveal that where creep is the dominant erosive process, the greatest removal of material occurs on the upper parts of the hillslopes. Accordingly, the profiles were separated into concave, straight or convex segments, and stake exposure on each segment was tabulated. The average slope inclination and stake exposure for the three slope segments are as follows:



5-14 Elbows developed in roots of annual and perennial plants at Montrose by seasonal creep. Note that the elbow is developed in that part of the root nearest the ground surface (from Schumm, 1964).

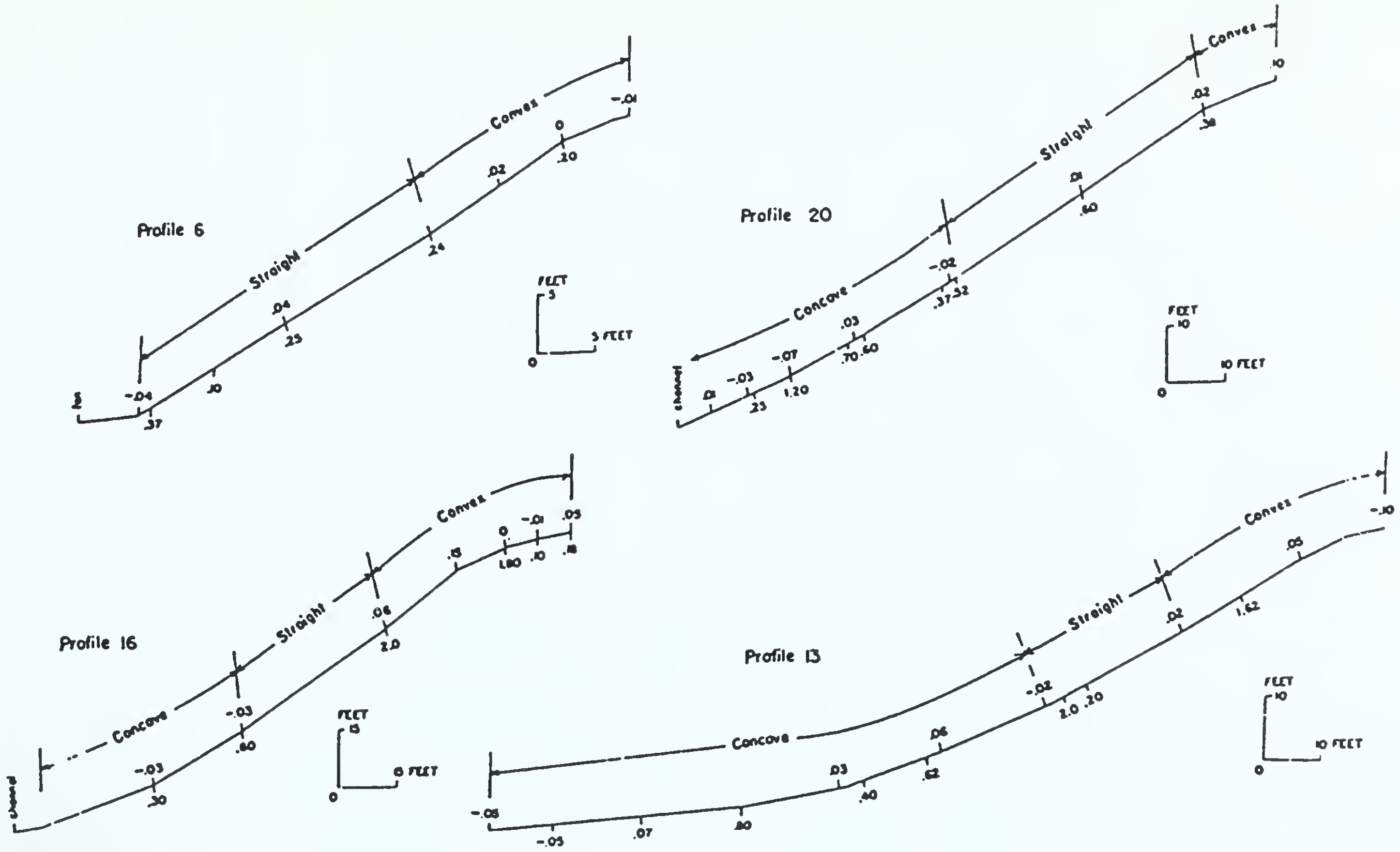
	Slope segments		
	Convex	Straight	Concave
Average stake exposure (ft.)	.022	.025	.002
Average slope (%)	36	71	46
Number of stakes	46	15	25
Stakes buried (%)	30	20	50

Stake exposure on the upper convex parts of the profiles is ten times greater than on the lower concave segments of the profiles (Fig. 5-15). This difference is statistically significant and occurs in spite of somewhat steeper average slopes on the concave segments. The steep straight slope segments have an average stake exposure of the same magnitude as the convex segments, and it is on these steeper portions of the slope that maximum marker movement occurs (Figure 5-15). The reason for the absence of a relationship between average stake exposure and slope inclination is clear, for on slope segments of equal inclination, significant erosion is occurring near the slope crest, but there is only minor erosion or deposition at the slope base.

The lower concavity is not entirely a depositional feature, for bedrock is close to the surface. Rather, erosion on this concave segment is hindered by the movement of sediment, eroded from the straight and convex segments, across it.

Seasonal Erosion

The typical concave-convex hillslopes developed on the Mancos Shale are, fashioned primarily by creep. An increase in summer precipitation or a decrease in winter precipitation, however, will probably permanently reduce the infiltration rates on the slopes, and runoff would become increasingly important. If this were to occur the slopes would be transformed by the action of rills and sheetwash. Observations



5-15 Hillslope profiles showing convex, concave and straight segments. Numbers above the profiles indicate total stake exposure in feet from Sept. 1958 to Sept. 1961. Numbers below the profiles indicate total marker movement in feet during same period (from Schumm, 1964).

elsewhere suggest that under these circumstances erosion will be greatest on the steeper segments of the slopes. Hadley and Toy (1977) used a rainfall simulator to apply 5 storms (intensity 1.85 in/hr for 42 minutes) on Badger Wash slopes. In contrast to Schumm's (1964) results they found that erosion was twice as great on straight slopes (0.054 ft) than on convex (0.023 ft) or concave (0.028 ft) slopes. Based upon the annual changes of slope characteristics five storms of this magnitude would change the process from creep to surface runoff with a major increase of erosion on the straight slopes.

As an indication of the potential for high erosion and salt production from hillslopes in Badger Wash, a fortunate occurrence in 1964 provided Hadley and Lusby (1967) the opportunity to evaluate the effect of a major storm on the as yet relatively uncompacted soil surface. During August 12, 1964 a total of 1.1 inches of rain fell during a six-hour period and 0.8 inches fell during the first thirty minutes of the storm. Prior to this storm rainfall was negligible, and the soil surface was loose and relatively uncompacted. Observations following the storm showed that much of the uncompacted material on the hillslopes was removed. There was a dramatic exposure of stakes as a result of erosion and compaction during that storm. Their calculation based on stake exposure was that 0.11 acre foot of sediment was eroded during that storm, and a resurvey of the reservoirs at the mouth of the small drainage basin showed that .09 acre feet of sediment was delivered to the reservoir. Considering the possibilities for error, this is good agreement, and their data indicate that during a storm of this sort when the soil is loose there is significant erosion of the slopes, and sediment is moved readily downstream.

Lusby (1977) used a sprinkler system similar to that of Shen et al (1981) to apply simulated precipitation to two small areas on the Mancos Shale in Badger Wash. Rainfall was applied to the two areas for a total of 5 applications as follows: Two in September 1971, two in June 1972, and one in September 1972.

Of most interest is the comparison of runoff and sediment yields for spring and fall conditions that is, the runs in Sept. 1971 and June 1972 as follows:

	Basin 1			Basin 2		
	September	June		September	June	
		dry	wet		dry	wet
runoff	0.31	0.34	.38	0.18	0.21	0.39
sediment yield	0.83.	1.74	1.36	0.55	1.28	1.44

Although runoff was almost identical in September and June, the friable surface of the Mancos Shale in spring yields twice the sediment. However, the runs in June on a previously wetted and presumably compacted surface showed an increase in runoff but a decrease of sediment yield for Basin 1 and a large increase of runoff with a much smaller increase of sediment yield for Basin 2. These results illustrate the difficulty in obtaining valid results for short term stretches on soils that change seasonally, but they do emphasize the importance of annual changes of soil surface properties on the Mancos Shale.

Hydrology of Mancos Shale Hillslopes

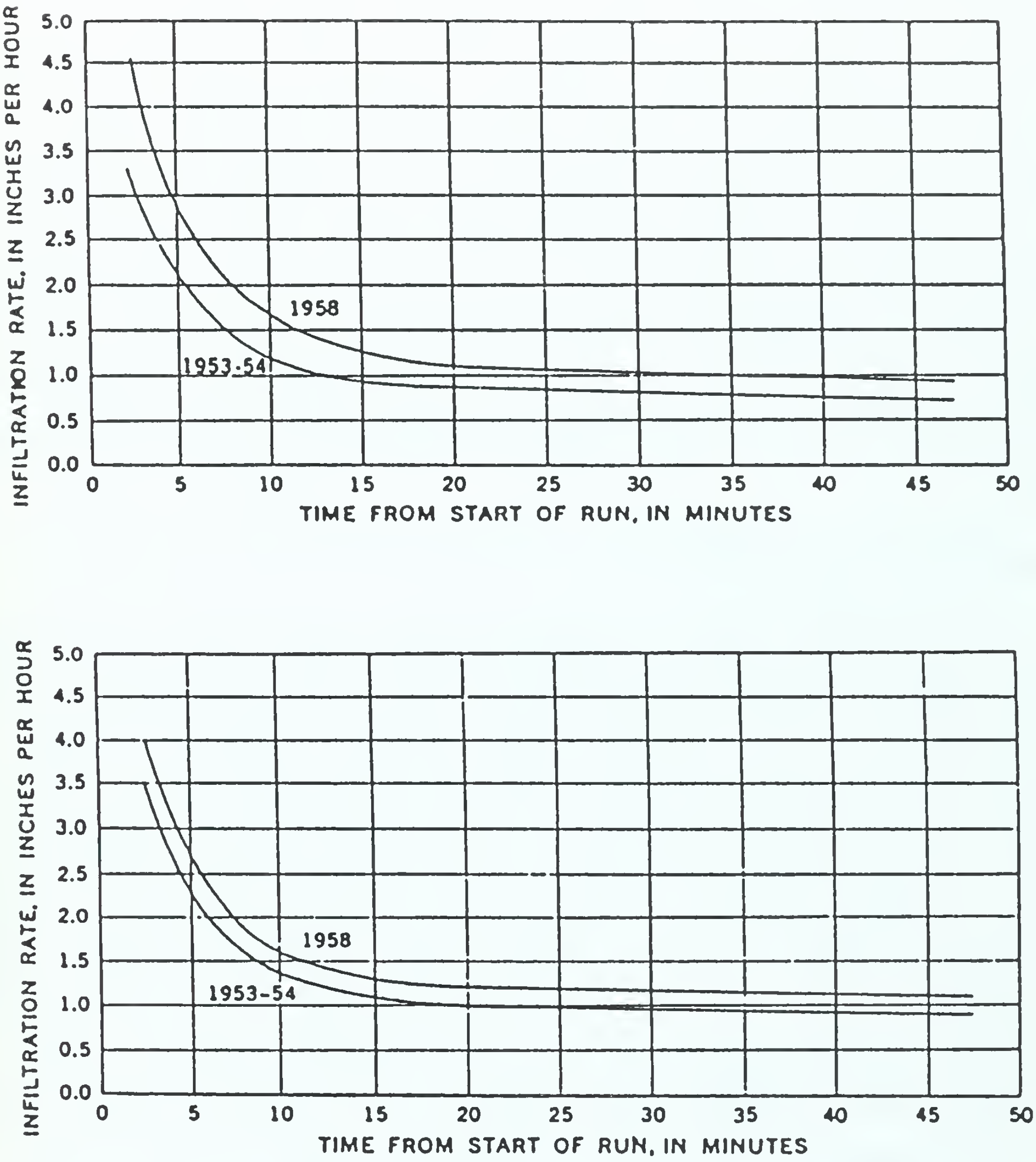
Data on the hydrologic characteristics of drainage basins on the Mancos shale have been collected for several small areas in Badger Wash. Eight-year records are available for runoff and sediment yield. In addition, two series of infiltration measurements were made with a Rocky Mountain infiltrometer in 1953-1954 and 1958 (Lusby et al, 1963). These data can be used to indicate how the seasonal changes in soil characteristics affect the hydrology of the slopes and the drainage basins as a whole.

Infiltration Capacity

The measurements of stake exposure suggest that infiltration capacity of the soil varies greatly during the annual cycle of loosening and compaction. The photographs show a surface capable of a high infiltration capacity in the spring (Figures 5-5 and 5-7) and a relatively lower infiltration capacity in the fall (Figs. 5-4 and 5-6). Infiltration rates were measured by the Forest Service at Badger Wash in the fall of the years 1953, 1954, and 1958. As these measurements were all made in the fall, it is impossible to obtain the annual range of values for rate of infiltration.

The infiltration rates measured in 1958 were significantly higher than those measured in 1953 and 1954 (Fig. 5-16). On the ungrazed watersheds infiltration rates increased from 0.89 to 1.12 inches/hour for the last 20 minutes of the dry runs and from 0.67 to 0.89 inch/hour for the last 20 minutes of the wet runs (Lusby et al, 1963). In addition, the water absorbed before the occurrence of runoff almost doubled, increasing from 0.19 to 0.35 inch. Since significant increases in infiltration rates also occurred on the grazed watersheds, the change could not be attributed solely to land use. A check of precipitation data seems to offer an explanation. From April through November 1953, when the infiltration rates were first measured, 6.55 inches of precipitation were recorded at the Fruita weather station. From April through October 1954, when the 1953-54 infiltration measurements were completed, 4.78 inches of rain fell at Badger Wash. However, only 1.94 inches of rain fell at Badger Wash from April through September 1958, when the second set of infiltration rates was measured. Thus, following the winter periods of soil loosening, only about 1/3 as much rain fell in 1958 as in the summers of 1953 and 1954 (U.S. Weather Bureau, 1953-1961). This small amount of precipitation caused relatively less compaction of the surface, and the increase of infiltration rates between 1953-1954 and 1958 may be explained in this manner. In spite of the compaction and surface sealing after 1.94 inches of rain, the surface absorbed 0.16 inch more water before runoff began in 1958 than in 1953-1954, and the infiltration rate was 0.23 inch/hour greater in the ungrazed watersheds.

Seasonal variations of infiltration rates have been reported by Horton (1940) and Horner and Lloyd (1940). Their research indicated that maximum infiltration rates occurred during the midsummer months as a result of the activity of soil fauna. Dreibelbis (1949) reported that in Ohio infiltration is retarded in the spring by frost penetration of



5-16 Average dry-run infiltration curves for (a) grazed plots and (b) ungrazed plots on the mixed soil type (from Lusby et al, 1963).

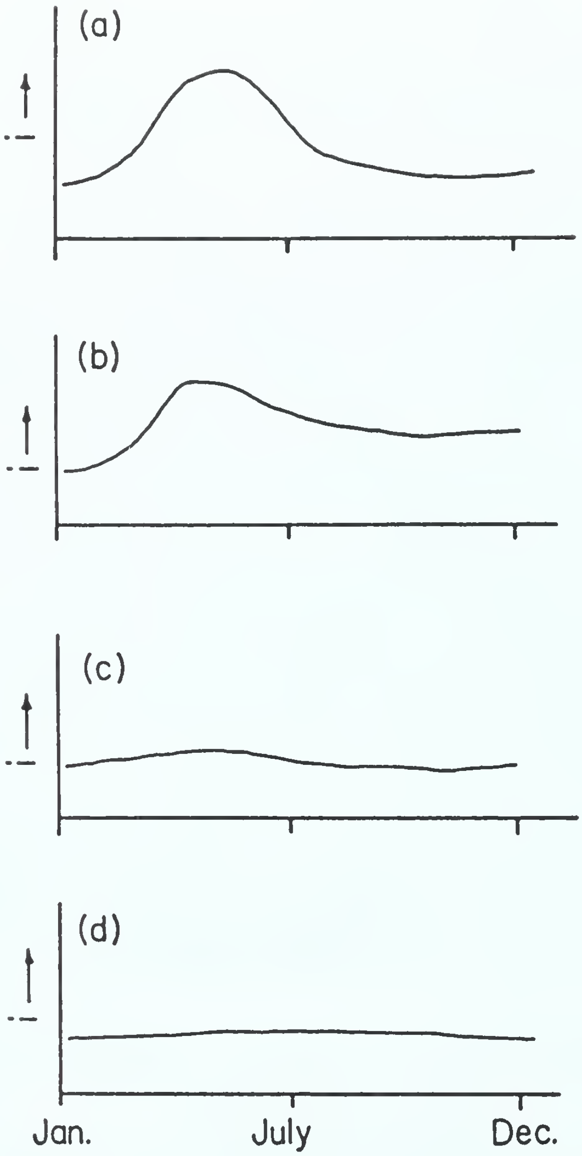
the soil, but on the poorly vegetated Mancos shale hillslopes, infiltration rates are maximum in early spring before the rains begin.

The effects of frost action in loosening the soil can be important on the bare soils of semiarid and arid regions. Infiltration capacity may vary annually as illustrated in Fig. 5-17 for semiarid areas underlain by the Mancos shale and similar formations. The seasonal variation of infiltration capacity illustrated in Fig. 5-17a will occur only for a year of normal precipitation. A dry winter will not cause an increase in infiltration capacity (Fig 5-17c, d), and a dry summer will not cause a decrease in infiltration capacity (Fig. 5-17b, d). Some support is given to these diagrams by the variations of stake exposure with varying seasonal precipitation at Badger Wash and Montrose (Schumm, 1964).

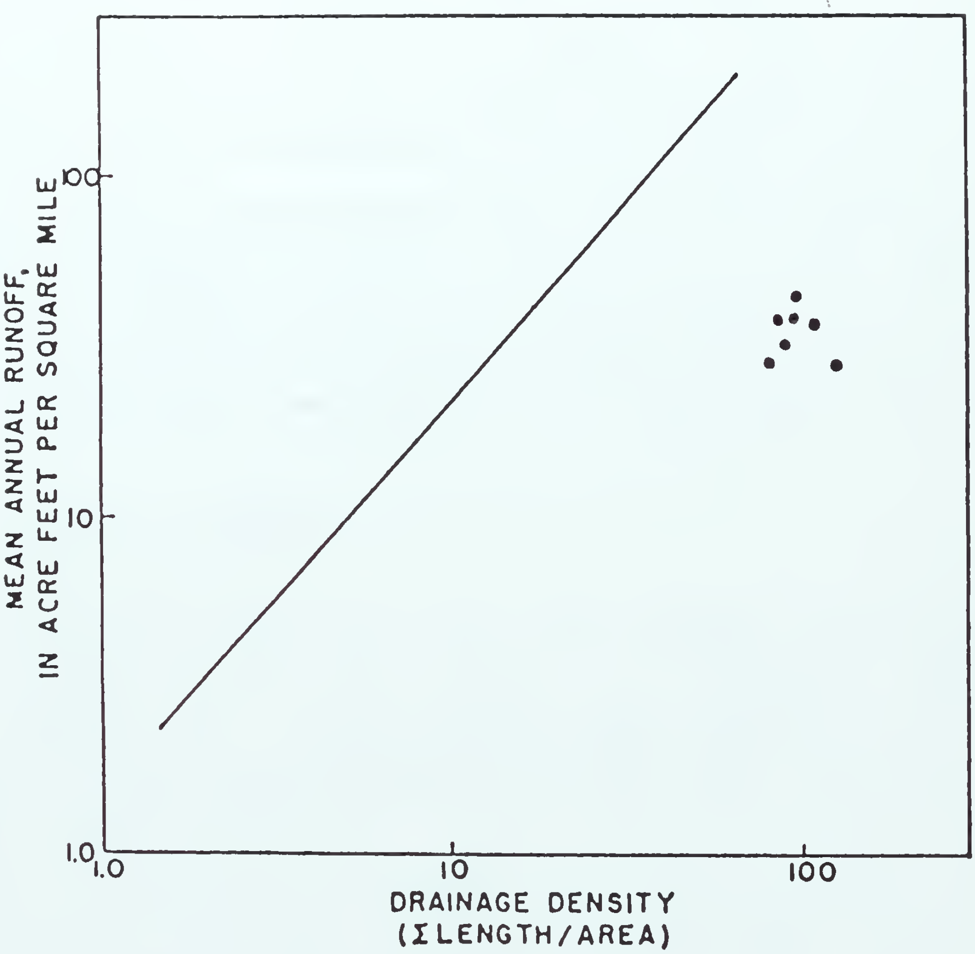
Sediment Yield and Runoff

As infiltration capacity is high on Mancos Shale slopes during early spring rains, the Badger Wash drainage basins should yield less runoff and sediment than drainage basins without seasonal changes of infiltration capacity. In fact, when average annual runoff is plotted against drainage density (Fig. 5-18) the Badger Wash drainage basins plot below the regression line which was established for small drainage basins in Wyoming (Hadley and Schumm, 1961; Schumm and Hadley, 1961). When average annual sediment yield for the Badger Wash drainage basins is plotted against relief-length ratio (Fig. 5-19), they plot reasonably close to the regression line, which was established for a number of drainage basins in Wyoming, Utah, and New Mexico. Thus, although runoff is low, sediment yield rates are about normal for this type of topography. Salt yield is about 3.8% of sediment yield, as measured in three of the Badger Wash drainage basins (Jackson et al, 1984 p. 10).

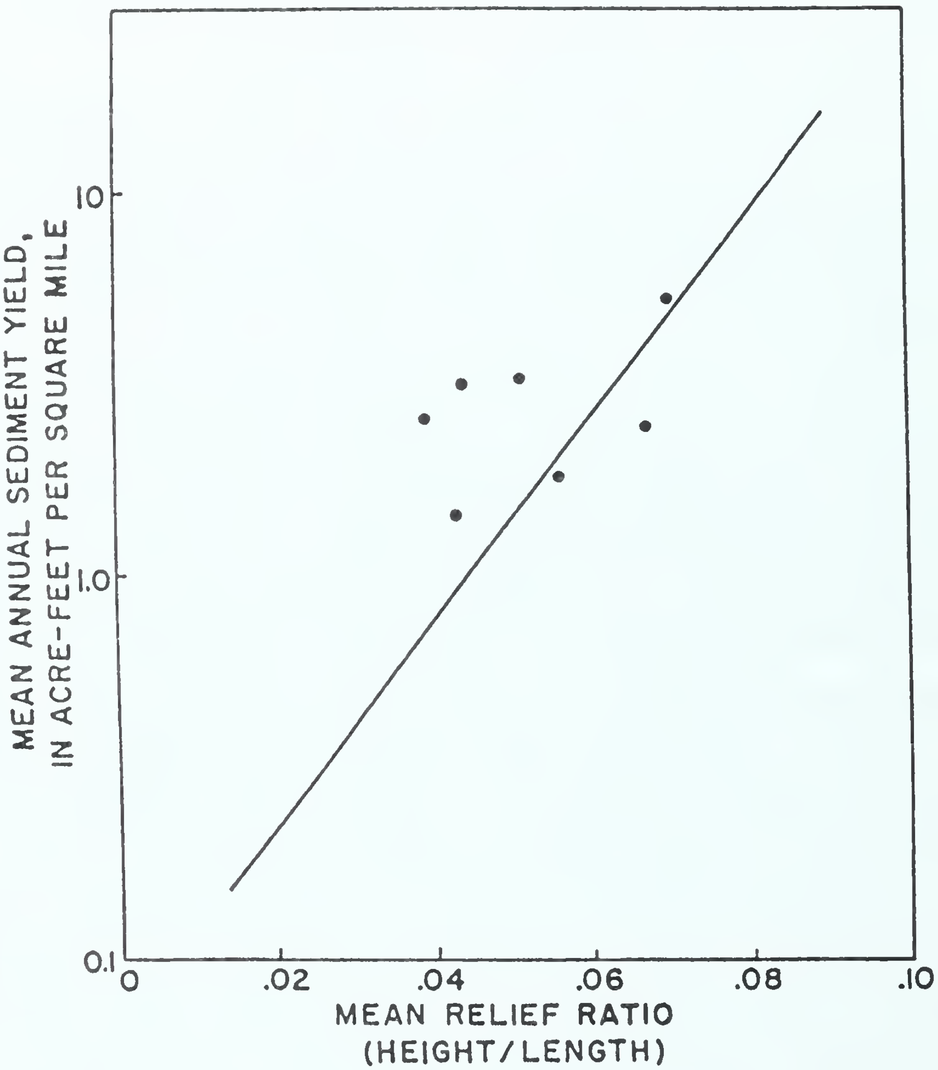
A significant percentage of the total area of the Badger Wash and Montrose study areas is composed of pediments and alluvial valley floors as noted by Johnson (1982). The seasonal changes noted on the slopes do not occur to the same extent on these flat surfaces. Therefore, the changes of seasonal infiltration capacity on the slopes can be applied only in a general way to an entire drainage basin.



5-17 Diagrams illustrating hypothetical seasonal changes of infiltration capacity on Mancos Shale Hillslopes. (a) normal precipitaiton, infiltration capacity increases during winter and decreases during spring and summer; (b) normal winter precipitation followed by a dry spring and summer, infiltration capacity increases during winter but does not decrease during spring and summer; (c) dry winter followed by normal spring and summer precipitation, infiltration capacity remains essentially constant during winter but shows a decrease in the spring and summer precipitation; (d) dry winter followed by dry spring and summer, infiltration capacity remains essentially constant after soil was compacted during previous summer (after Schumm and Lusby, 1963).



5-18 Comparison of Badger Wash runoff data to regression line that was established between runoff and drainage density for other small drainage basins in a semiarid climate (from Schumm and Lusby, 1963).



5-19 Comparison of Badger Wash sediment yield data to regression line established between sediment yield and relief-length ratio for other small drainage basins in a semiarid climate (from Schumm and Lusby, 1963).

To determine whether the seasonal effects on runoff from the small watersheds are measurable, all storms that produced more than 0.1 inch of rain in Badger Wash, from April through October for the years 1954 through 1961, were examined. In Table 5-2 the storms are grouped by 0.1 inch increments for a spring period (April through June) and a fall period (August through October). Precipitation and runoff for the storms of each period were averaged in this manner to reduce possible variations in runoff caused by differences in precipitation intensity. Although discrepancies exist between individual storms during some years, average runoff and the ratio of runoff to precipitation are consistently larger during the fall period for all sizes of storms (Table 5-2).

Two factors which may have an effect on these ratios, intensity of precipitation and antecedent moisture conditions, were also investigated. Although individual storms of slightly greater intensity occurred more frequently during late summer, these storms occurred too infrequently to cause the difference found between average runoff and the runoff-precipitation ratios of Table 5-2. Individual storms of high intensity occurred during the spring, but, as expected, total unit runoff was less from these high-intensity spring storms than from fall storms of comparable intensity. Differences in rainfall intensity, therefore, are not great enough to cause the disparity between average runoff as measured in the spring and in the fall at Badger Wash.

The effect of antecedent moisture at Badger Wash is more difficult to evaluate, but for the storms listed in Table 5-2 it is believed to be negligible. During the early part of the spring period there may be some subsurface moisture, which would affect the infiltration rate during extended rains, but most rains in the area are of short duration at all seasons of the year.

The large differences in runoff between the spring and fall periods must therefore be attributed predominantly to the large differences in soil characteristics (Figures 5-4 and 5-7) rather than to differences in intensity of precipitation or antecedent moisture conditions. However, the dominant factor, which causes the seasonal soil changes, is the lack of vegetational cover. The seasonal changes in turn have a critical effect on drainage basin hydrology. Elsewhere at higher altitudes where rainfall is greater, Mancos shale hillslopes are well vegetated, and, although they show evidence of mass movement, slumping and creep induced by frost action in the soil is probably of minor importance. The seasonal variation of soil characteristics is reduced by the presence of vegetation.

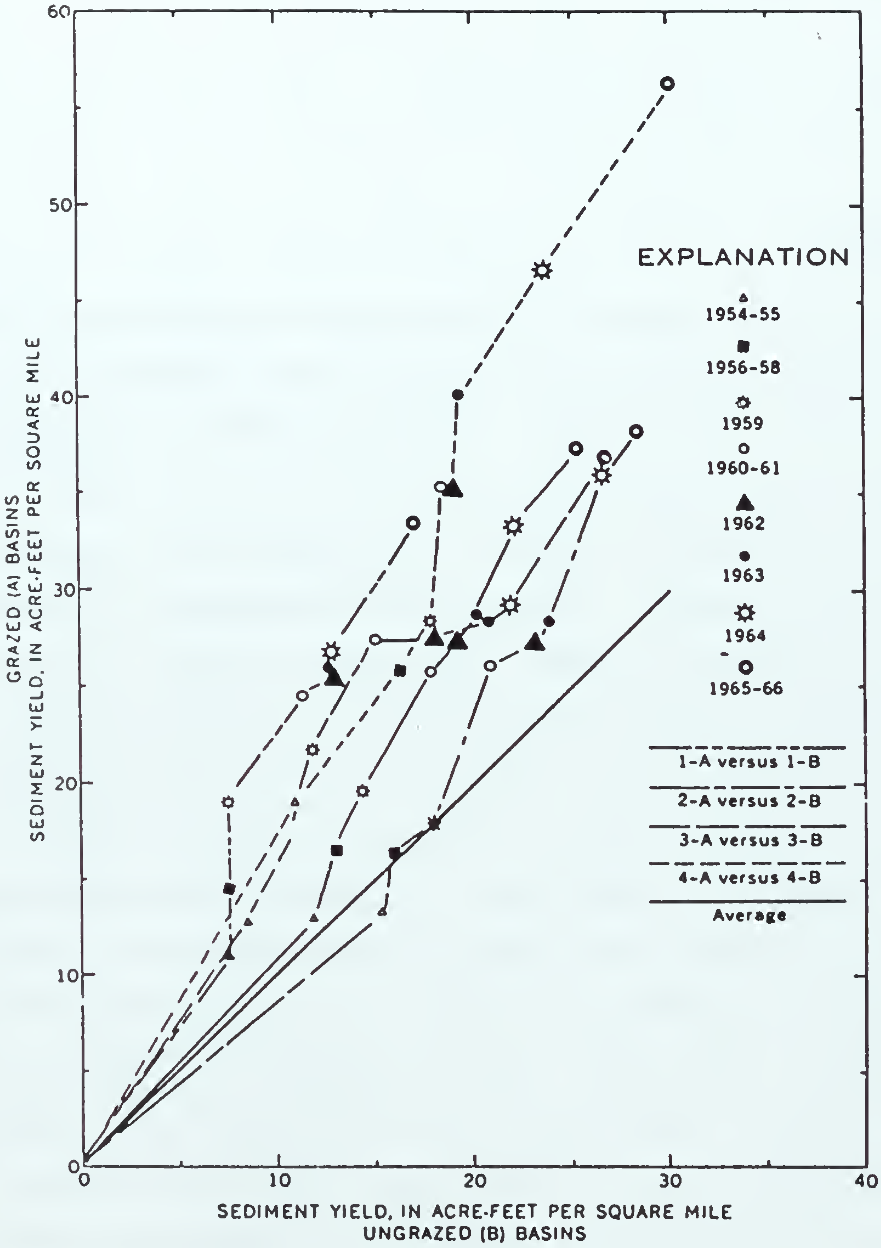
Effect of Grazing

During the first 5 years of the Badger Wash study little of significance emerged because two of the years were extremely dry and precipitation was highly variable. During this period resurveys of channel cross sections showed that a significant source of sediment was channel erosion (Lusby et al, 1963).

The second report on the Badger Wash study covered the period 1953 to 1966 (Lusby et al, 1971). At the end of thirteen years significant differences were beginning to appear. For example, sediment yields from the ungrazed basins were significantly less after 1955 (Fig. 5-20).

The final report on the twenty-year study, which ended in 1973, was published in 1979 (Lusby, 1979). In order to evaluate the results of the study with regard to changes in runoff and sediment yield, it is necessary to remember that there were four sets of paired watersheds, one of each of the paired watersheds was fenced during the winter of 1953, and it was not grazed afterwards. From 1954 through 1965 the remaining watersheds were grazed by cattle and sheep from November 15 to May 15. Starting in 1966 grazing was by sheep only, and the period of use was from November 15 to February 15. In addition, some watersheds were grazed every other year instead of each year. The elimination of grazing during the period 1953-65 resulted in a reduction of runoff by about 25% and a reduction of sediment yield of about 35%. During 1966 through 1973, ungrazed areas were yielding 40% less runoff and 63% less sediment than was produced under the original conditions.

Grazing by sheep only from November 15 to February 15 each year reduced runoff from the grazed areas by 29% of that of the base period. Areas grazed by sheep only from November 15 through February 15 every other year produced 20% less runoff than during the base period, and



5-20 Mass diagrams of sediment yield for four pairs of watersheds at Badger Wash (from Lusby, Reid and Knipe, 1971).

both reductions in runoff were accompanied by similar reductions in sediment yield (Lusby, 1979). The greatest reduction in erosion because of grazing controls was noted in the steeper drainage basins (Lusby, 1979).

Experimental Studies

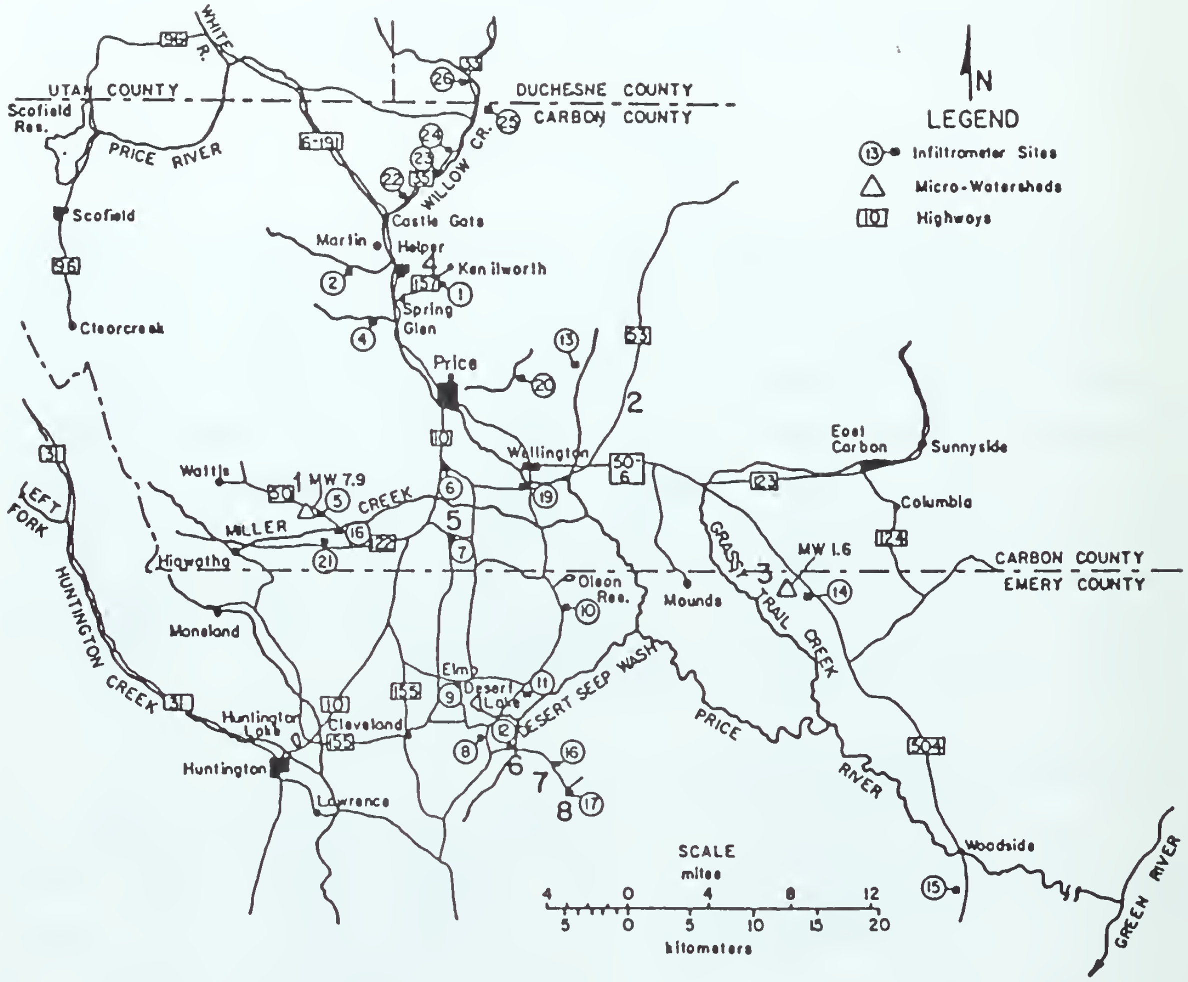
In an effort to develop a better understanding of erosion processes and salt production on the Mancos Shale terrain several experimental studies were performed in very small areas. For example, Ponce (1975) attempted to quantify salinity production from small plots and in micro-watersheds of the Price River Basin. Shen et al (1981) generated runoff on Mancos Shale hillslope segments in order to evaluate surface runoff and salt production, whereas White (1977) focused attention on runoff generation in small channels in the Price River basin that are in contact with or are incised in Mancos Shale. The design, procedure and scale of the studies differed considerably.

Experimental Design and Procedures

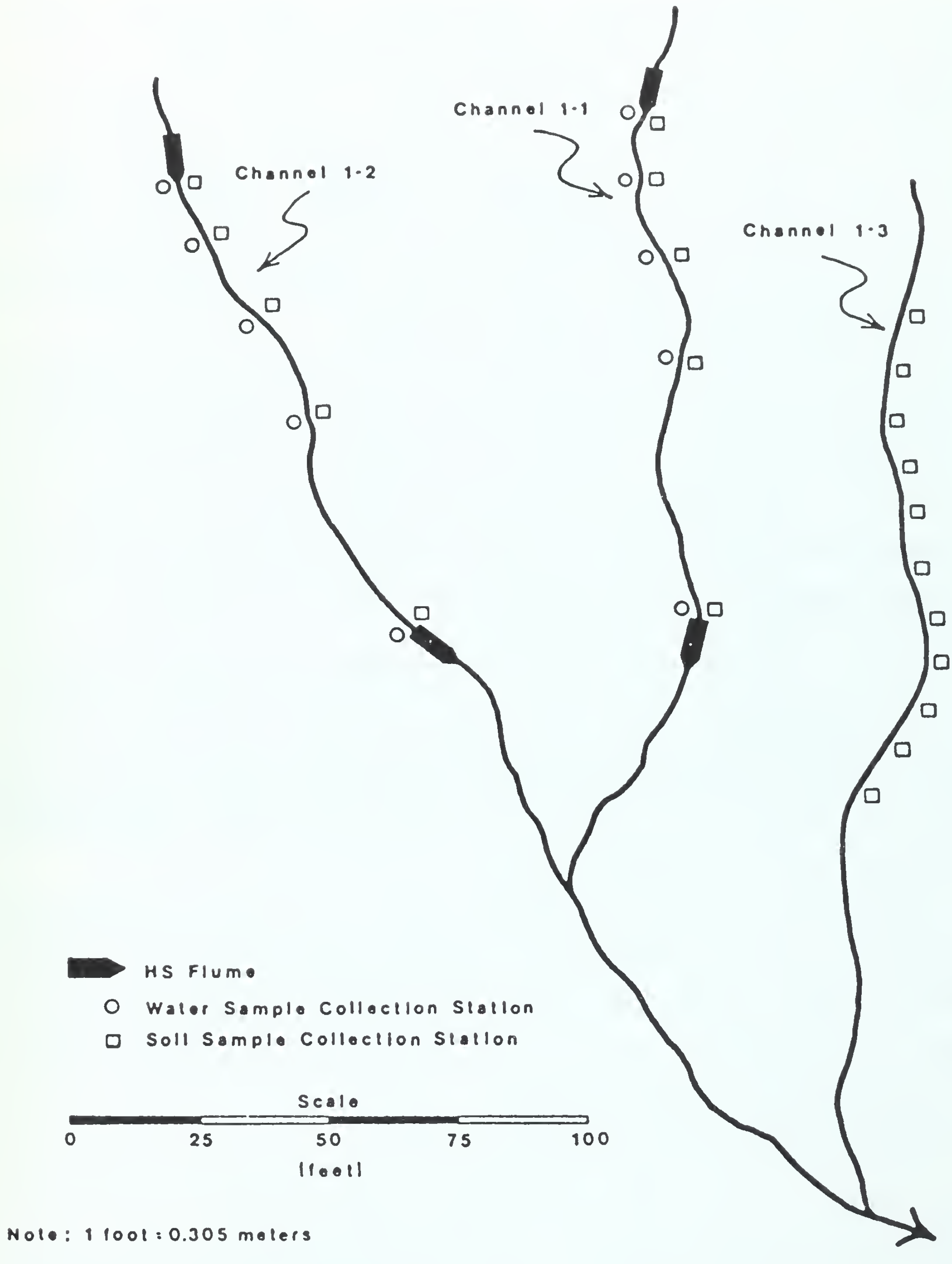
Ponce (1975) performed an elaborate set of field investigations on the Mancos Shale (Fig. 5-21), which included studies on small plots (0.23 m^2), on micro-watersheds (3.7 m^2) and on large (11.2 m^2) plots. The Rocky Mountain Infiltrometer was used as a rainfall simulator. It is portable and it can generate a reasonable range (25-125 mm/hr) of rainfall intensity. Simulated rainfall (distilled water) droplets fall 3-6 m before striking the ground with velocities exceeding 75 percent of their terminal velocity (for a median intensity of 75 mm/hr).

The role of four variables (plot length, rainfall duration and intensity, and antecedent moisture) on runoff salinity was investigated by Ponce. Plots and microwatersheds had a 5-15 percent slope and they were located on undivided Mancos Shale except for 3 microwatersheds that were located on the Upper Blue Gate member of Mancos Shale.

A series of experiments, whereby runoff (using water of 350-400 µmho/cm with hardly any sediment) was generaged in 30 m long channels, (Fig. 5-22) were undertaken by White (1977). The objective of this



5-21 Location of reconnaissance survey, large plots (circles) and micro-watersheds (triangles). Channels selected by White (1977) are denoted by large numerals (from Ponce, 1975).



5-22 Small-channel study site 1 (from White, 1977).

study was to determine channel contribution to solute yields. The channels were located close to the plots of Ponce (see Fig. 5-21) and their description is summarized in Table 5-3.

Sunday (1979) and Enck (1981) conducted two runoff experiments on Mancos Shale hillslopes in the Grand Valley, westernmost Colorado (Fig. 5-23, 5-24). Results from these experiments and from additional studies have been summarized by Shen et al (1981). Figure 5-25 depicts the experimental designs in both studies, and Table 5-4 summarizes the characteristics of hillslopes from their Study I.

Study I involved hillslopes that had a typically low vegetation cover and well defined rills near the bottom of the slope that provided cross slope variability. Water was supplied to the slopes from a perforated 10 cm PVC pipe that was placed near the head of the slope. A constant head tank was used to ensure constant discharge. Relatively high quality water, 450 μmho/cm @ 25°C and 100 ppm suspended solids was supplied by a local artesian well service.

The direct application of water at the top of the slope determined the flow conditions. Due to the micro-topography of any particular slope, the water was concentrated into a small area, rather than uniformly wetting the hillslope surface. Anastomosing overland flow was generated downslope of the pipe on all hillslopes except those steeper than 30° which were typically rilled.

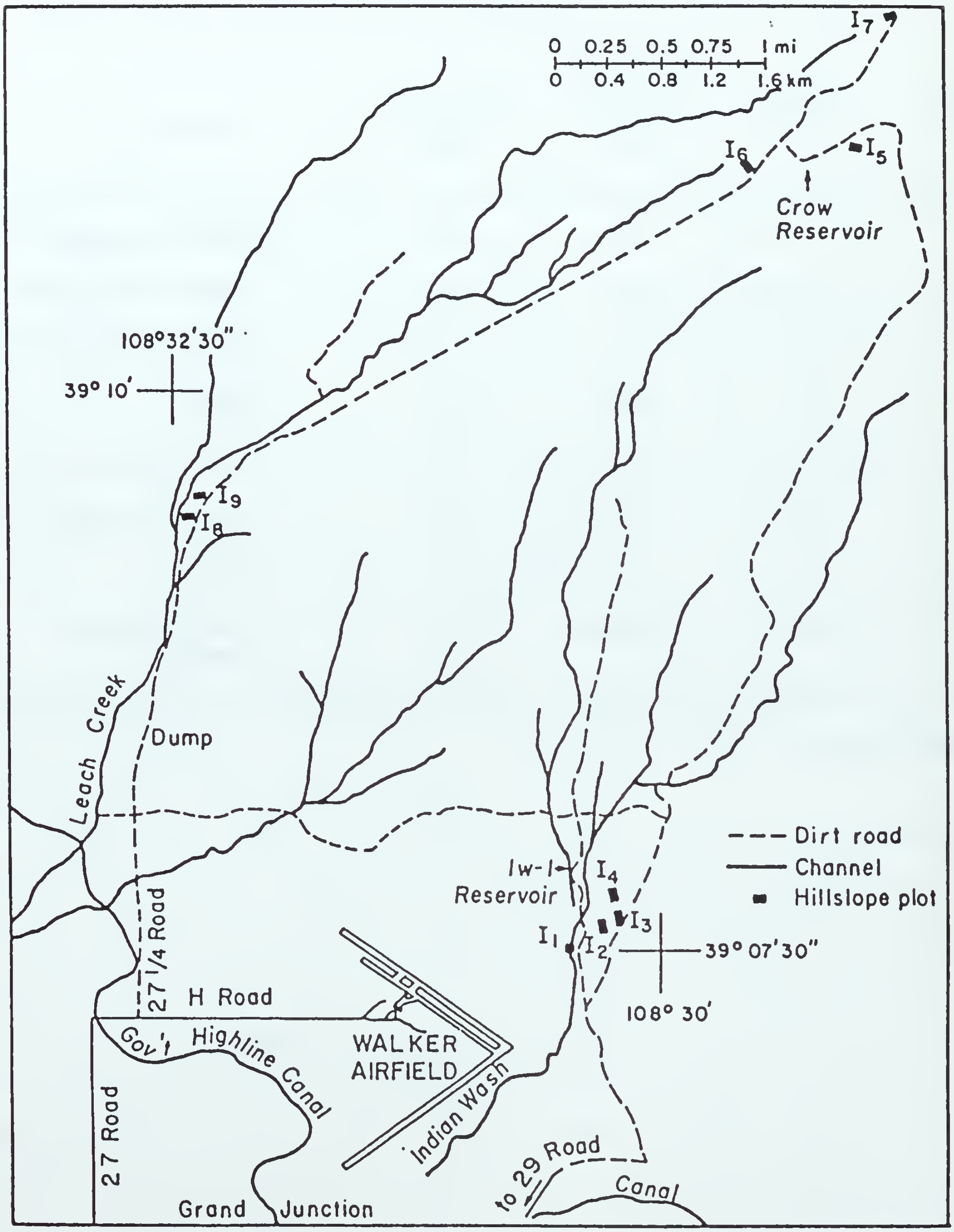
Samples were taken approximately 1.5, 4.5 and 9 m downslope (stations A, B and C, respectively) and also where the end of the slope entered a channel as well as further down-channel (stations D_1 and D_2). Sampling was continued for up to three hours after the leading edge of the flow reached the sampling station. At the B and C stations, samples were taken at two locations across the slope.

Hillslope Study II was conducted in the West and East Salt Creek Basins (Fig. 5-24). Small watersheds were selected and artifical precipitation was applied from a sprinkler system (Fig. 5-25b). Slope lengths varied from 11 to 22.6 m, and slope inclination was in the range 27-87 percent.

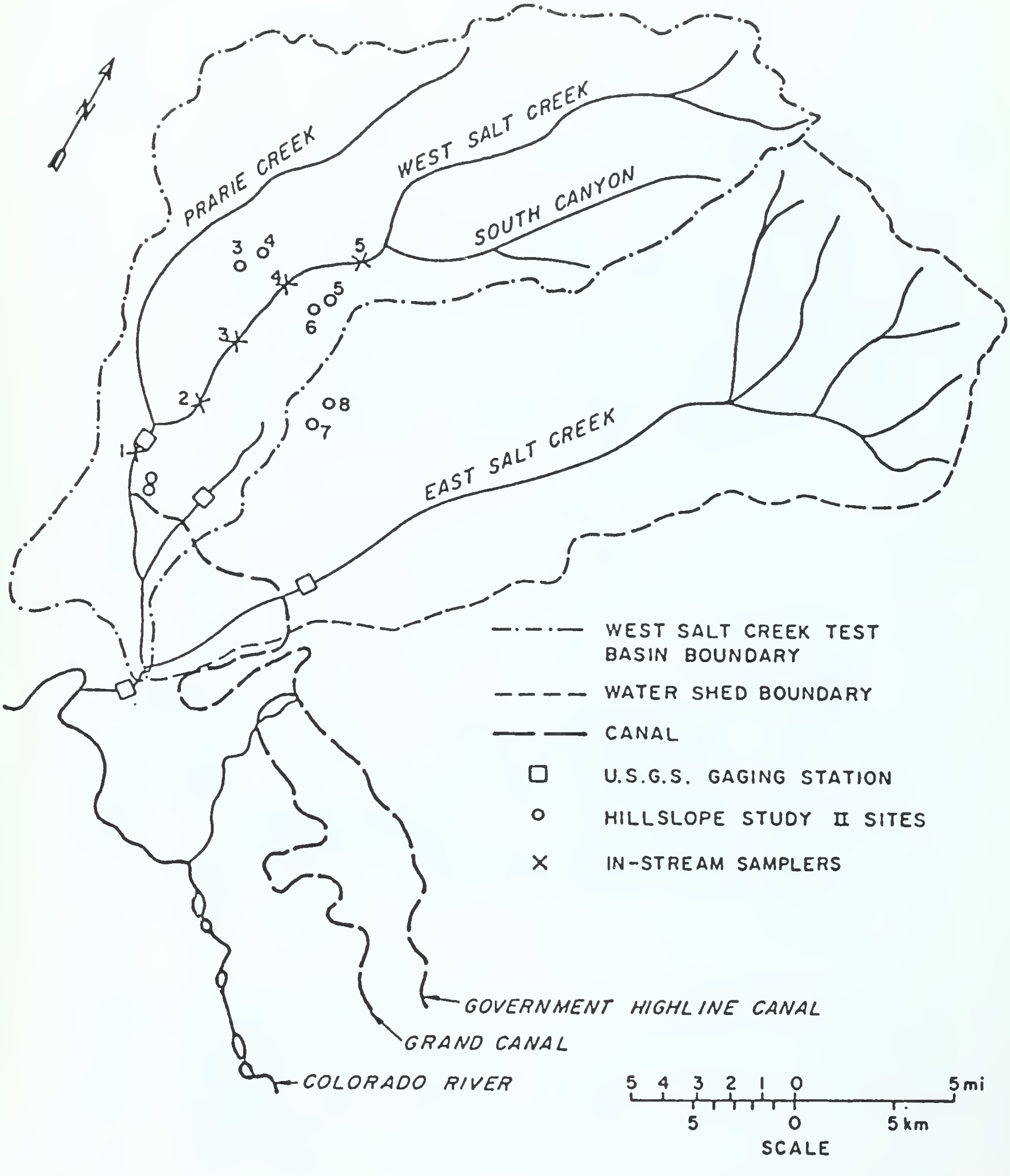
Table 5.3. Description of channels sampled during the Price River Basin channel study (after White, 1977).

Site Number	Channel Numbers	Length of Channel Studied (m)	Duration of Runs (min)	Geologic Type*
1	1-1,1-2,1-3	30	30	Upper Blue Gate
2	2-1,2-2,2-3	30	30	Mancos Undivided
3	3-1,3-2,3-3	30	30	Mancos Undivided
4	4-1	60	30	Masuk
5	5-1	90	60	Middle Blue Gate
6	6-1	30	30	Lower Blue Gate
7	7-1	30	50	Tununk
8	8-1	30	30	Cedar Mountain Formation

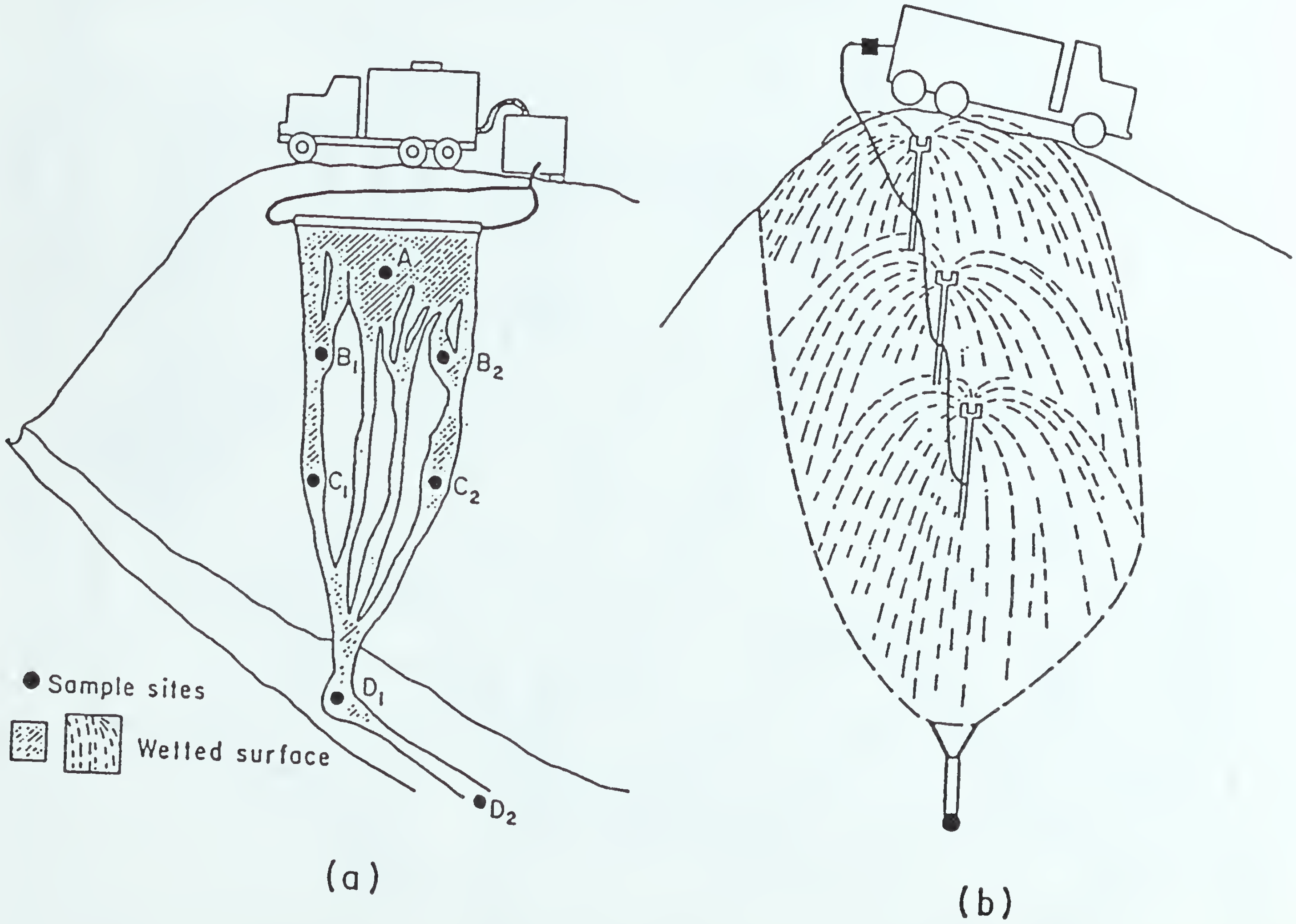
*Mancos Shale



5-23 Map showing the location of Hillslope Study I sites (after Shen et al, 1981).



5-24 Map of West and East Salt Creek Basins showing the location of Hillslope Study II sites (after Shen et al, 1981).



5-25 Typical field arrangements, Hillslope Studies I(a) and II(b) (after Shen et al, 1981).

Table 5.4. Generalized description of Hillslope Study I (after Shen et al, 1981).

Plot Number	Extent of Surface Covered by Calcareous Cemented Sandstone	Inclination from Station A to Station D_1 (percent)	Hillslope Faces	Disturbance	Remarks
I-3	extensively	62	S	off-road vehicle track at bottom	hummocky with few animal (gopher?) holes
I-4	extensively	31	N	off-road vehicle track at top and at bottom	same as I-3 more holes
I-5	hardly at all	62	E	undisturbed	two sandy strata rich in gypsum crystals
I-6	hardly at all	55	WSW	undisturbed	several holes between stations C_2 and D_1
I-7	somewhat	31	S	undisturbed	same as I-6, 10% vegetative cover, very hummocky
I-8	extensively	19	S	few cattle footprints	footprints serve as miniature ponds
I-9	extensively	12	WNW	few cattle footprints	footprints serve as miniature ponds

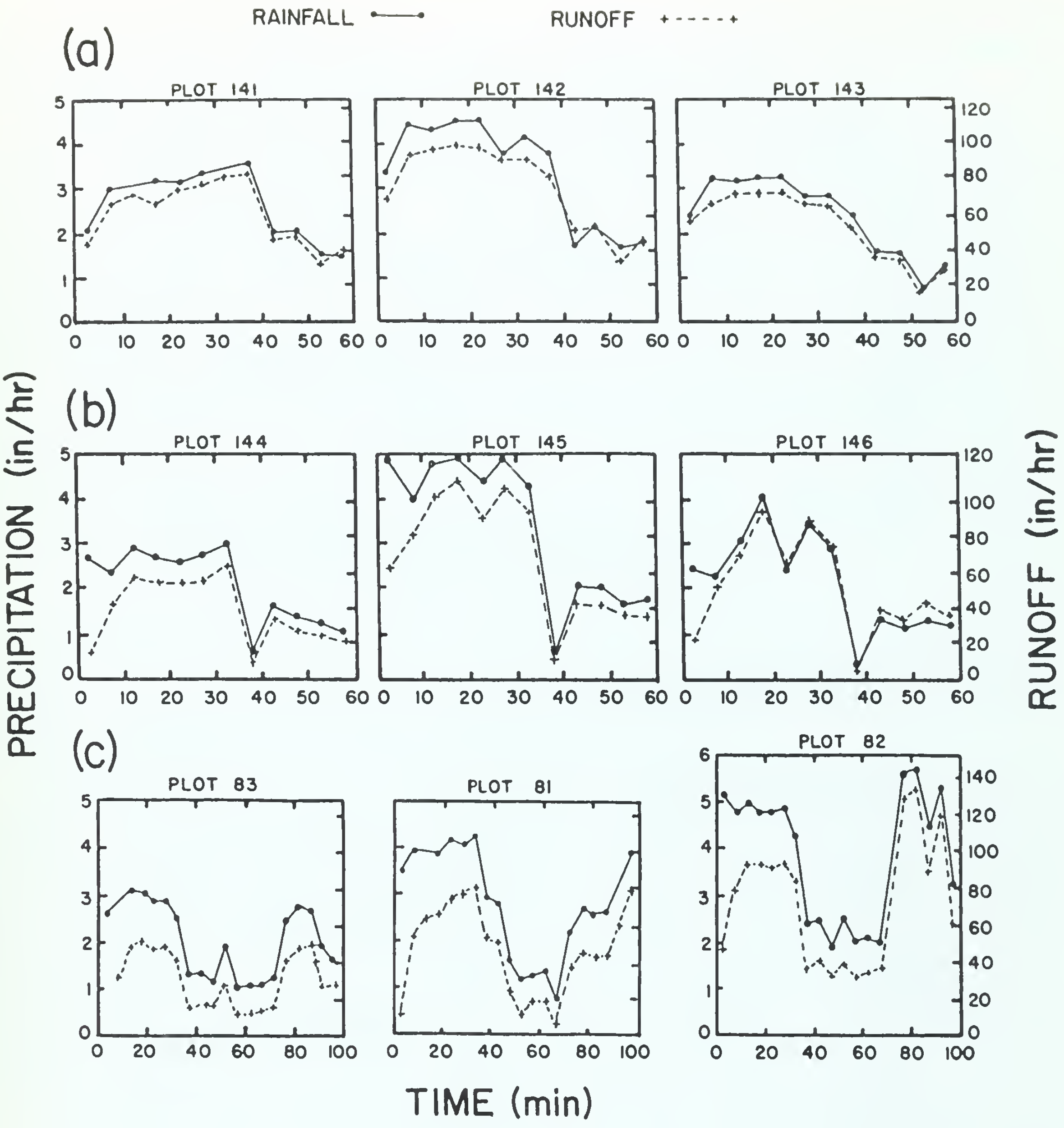
Runoff

The hydrologic response of Mancos Shale on the small relatively flat plots selected by Ponce (1975) to rainfall of varying intensities was very quick on his plots 141-143. Runoff-rainfall ratios exceeded 0.85 within 2 min from the onset of rainfall application, and they exceeded 0.5 during this period of time on the other plots (Fig. 5-26). The significance of such a quick response is that a thundershower intensity (90 mm/hr) lasting 2 min (3 mm total rainfall), a frequent event in the Upper Colorado River Basin, would produce considerable runoff from these surfaces. However, as the Badger Wash study shows, not all members of the Mancos Shale, nor overlying and underlying formations, are characterized by such high rates of runoff which reflect low rates of infiltration.

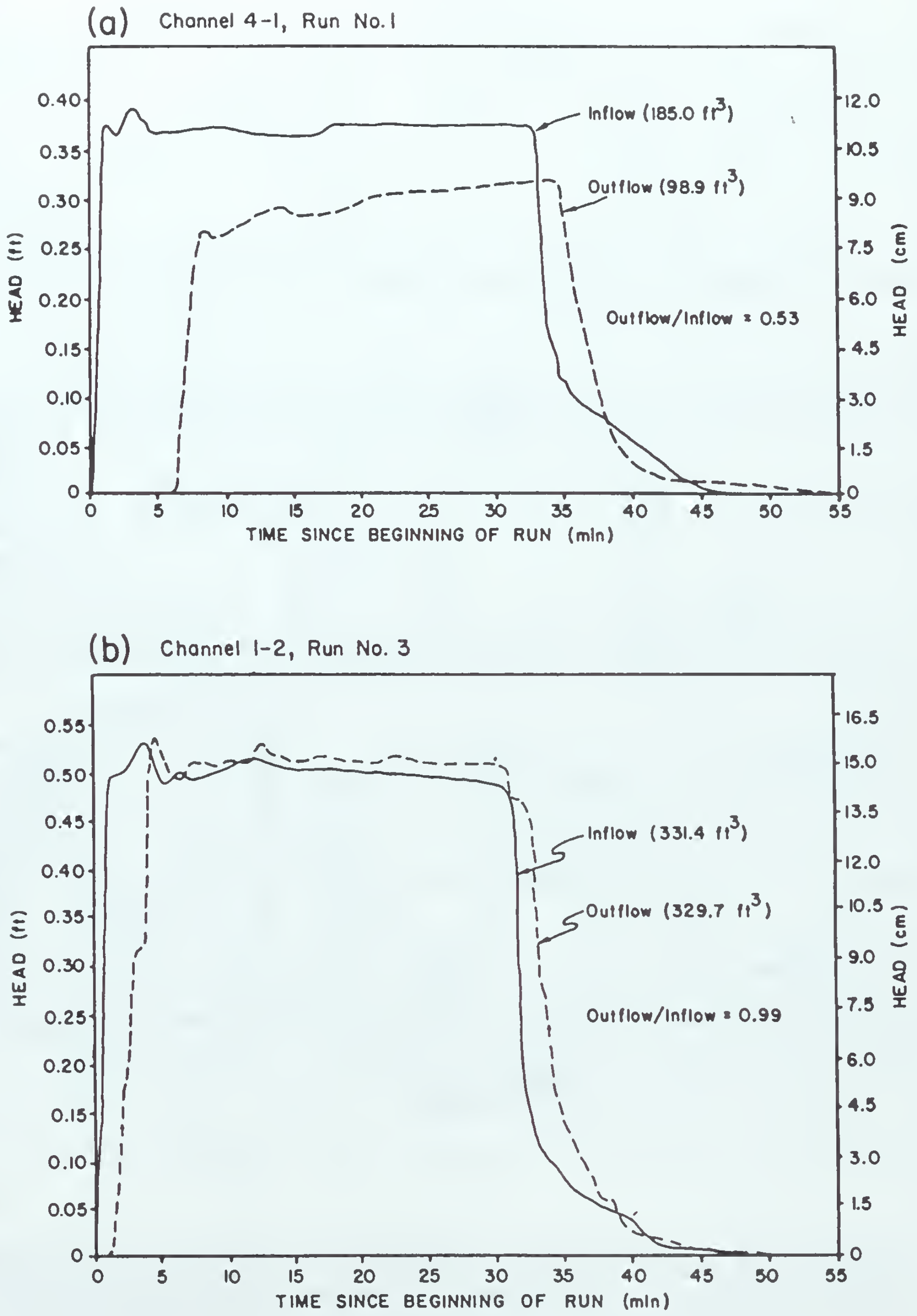
White investigated the yield of solutes by releasing water, which had been trucked to the site, directly into small channels (Fig. 5-22). Flow rates remained relatively constant for a single run, but they were varied between runs over a range of approximately 0.001-0.006 m^3 sec (0.05-0.20 cfs). The duration of runs (30-60 min) and the flow rates were presumed to be typical of the flows which would result from the short duration, high intensity storms which prevail during the summer months in the Price River Basin.

Seepage losses are naturally high in the gravelly alluvial channels that drain the Mancos Shale terrain, and they are high in first order bedrock channels due to jointing and fractures through which most of the seepage occurs (Fig. 5-27a). However, most bedrock channels draining Mancos Shale hillslopes will respond very quickly to rainfall (Fig. 5-27b).

The type of surface flow generated on Mancos Shale depends on the microtopography of the surface, hillslope inclination and rainfall intensity and duration. The steepest hillslopes (0.87) investigated by Shen et al (1981) were initially rilled and, therefore, anastomosing unconcentrated runoff was generated on these surfaces only in interrill areas (Study II), and it was completely absent in Study I except near the hillslope divide. Rills did not form at all on the 7^0 slope during



5-26 Hyetographs and hydrographs resulting from rainfall simulation. Plots (1.5m long) were located on Mancos Shale Undivided (a and b) and on the Upper Blue Gate Member (c) (after Ponce, 1975).



5-27 Inflow and outflow hydrographs for channels underlain by (a) Masuk Shale and (b) Blue Gate Shale resulting from direct runoff generation (after White, 1977).

the entire test period, but rilling commenced earlier, as hillslope inclination increased (Table 5-5).

The timing of rill formation listed in Table 5-5 should be carefully noted. Rills formed on hillslope I-8, but after a much longer time span than on the steeper slopes. Hillslopes I-8 and I-7 had only very shallow, surface rills, whereas on hillslopes I-3 and I-4 noticeable concentrations of flow developed and this was followed by rill development. The much steeper slope of I-6 had surface rills at four minutes and after five minutes there was no overland flow, only a few deep rills. Run I-5 was on a slope that was initially very rilled; the number of rills deepened substantially after eight minutes, and their total depth was 17.8-25.4 cm at the end of the run. The two steepest runs had mud and slug flows in the rills.

The flow generated by Ponce (1975) on plots and micro-watersheds was mainly unconcentrated due to the gentle hillslopes involved (0.05 on the smaller plots; 5-15 percent for the micro-watersheds) or else rilled to a depth not exceeding 3 cm for the micro-watersheds.

Salinity Variations: During Ponce's (1975) plot experiments (Fig. 5-28). EC remained low and constant for plots 141-143 and 146; it increased with time and reached a peak when the runoff rate was lowest (e.g. plot 144), and behaved rather erratically in several instances (e.g. plot 82). Note that EC tended to vary inversely with rainfall intensity on plots 82 and 83, and it remained constant in plots 141-143. Ponce suggested that these trends may be ascribed to different mechanisms of solute release, which will be discussed later.

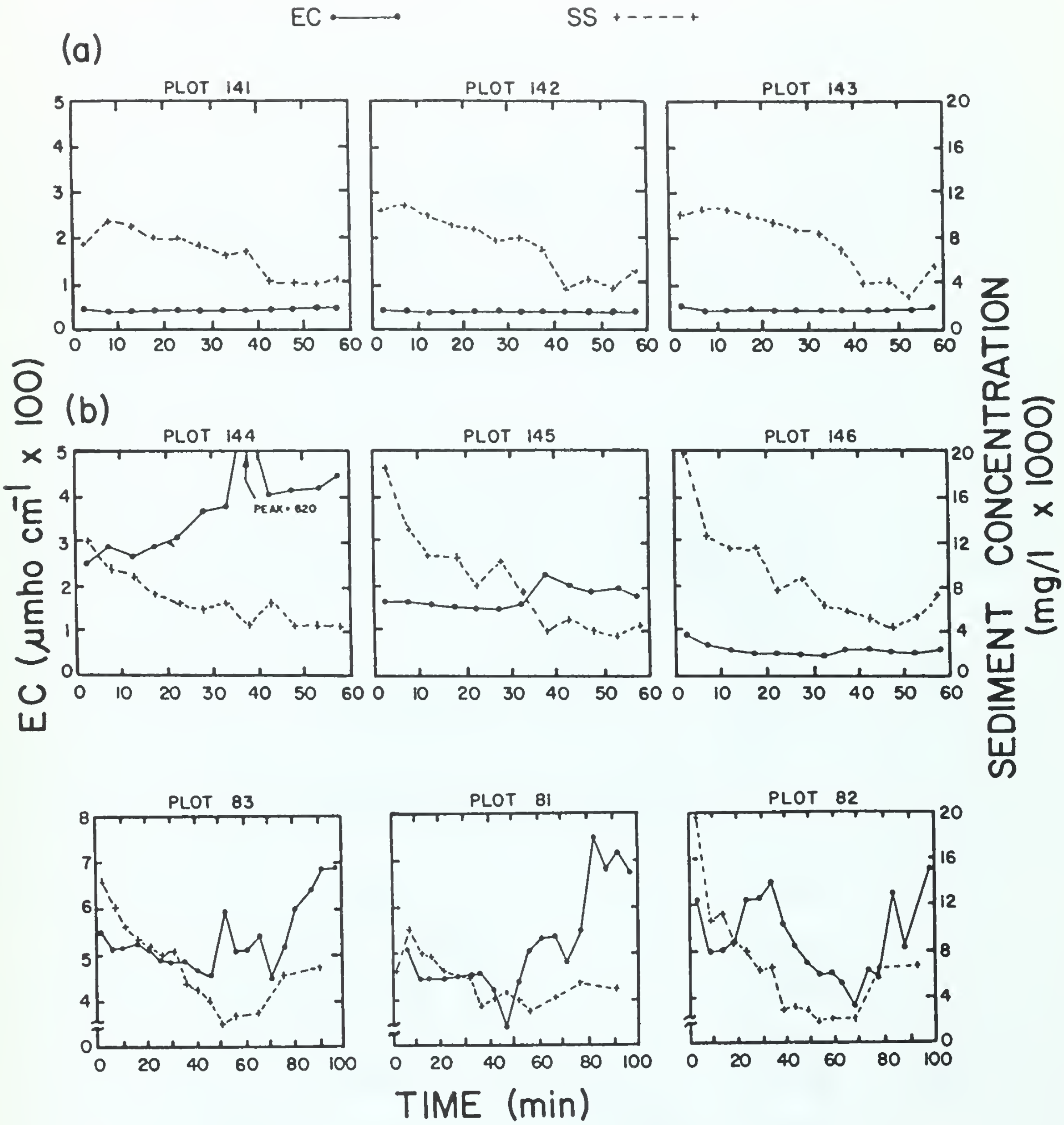
The trends of runoff EC depicted in Figure 5-28 also show that the release of solutes is minimal, as EC values are substantially lower than those in the waters of the Price and Green River. Similar temporal trends in EC were also observed in the micro-watershed study, although EC values were on average twice as high as those on the plots.

Shen et al (1981) also described the temporal variation of runoff salinity. The results from three selected hillslope experiments include both temporal and spatial trends in salinity (Fig. 5-29). Sample collection was initiated at each station with collection of the leading edge of flow and, therefore, the first data point for each station shifts to the right along the abcissa for stations A to D_2 (Fig. 5-24b).

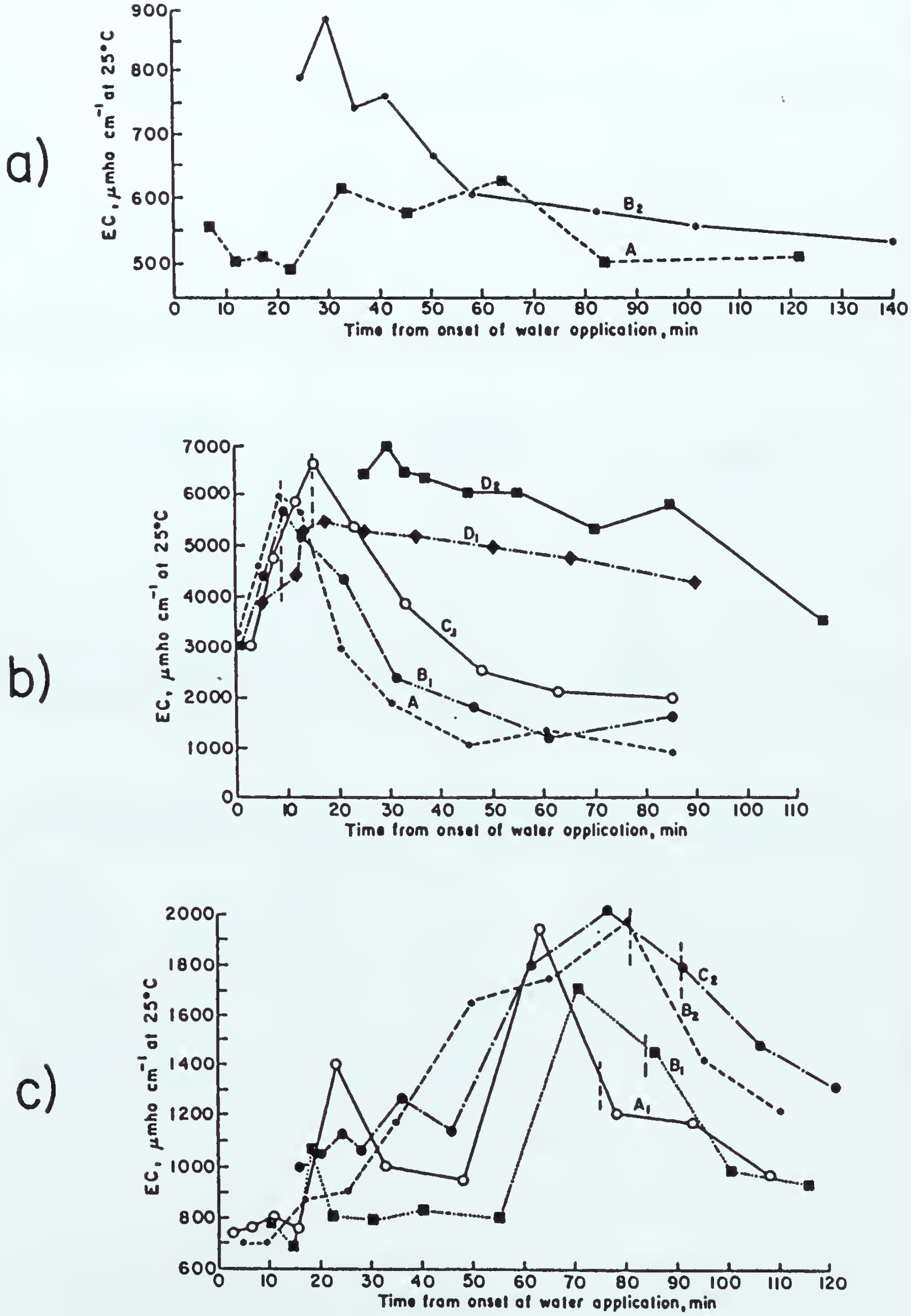
Table 5.5. Hillslope inclination and time to rill formation (after Shen et al, 1981).

hillslope	inclination (degrees)	(percent)	time to rilling (min)
I-9	7	12.3	
I-8	11	19.4	40
I-7	17	30.5	8
I-3	17	30.5	15-20
I-4	23	42.4	2-6
I-6	29	55.4	4-5
I-5	32	62.5	8-15[a]
II-8	15	26.8	25
II-1	16	28.7	16
II-7	20	36.4	25
II-6	20	36.4	16
II-3	25	46.6	15
II-4	30	57.8	
II-2	35	70.0	
II-5	41	86.9	

[a]initially rilled; reference is made to the time to rill entrenchment



5-28 Temporal variations of salinity (EC) and sediment concentration during the rainfall intensity-duration study. The respective hyetogtaphs and hydrographs are depicted in Figure 5-27 (after Ponce, 1975).



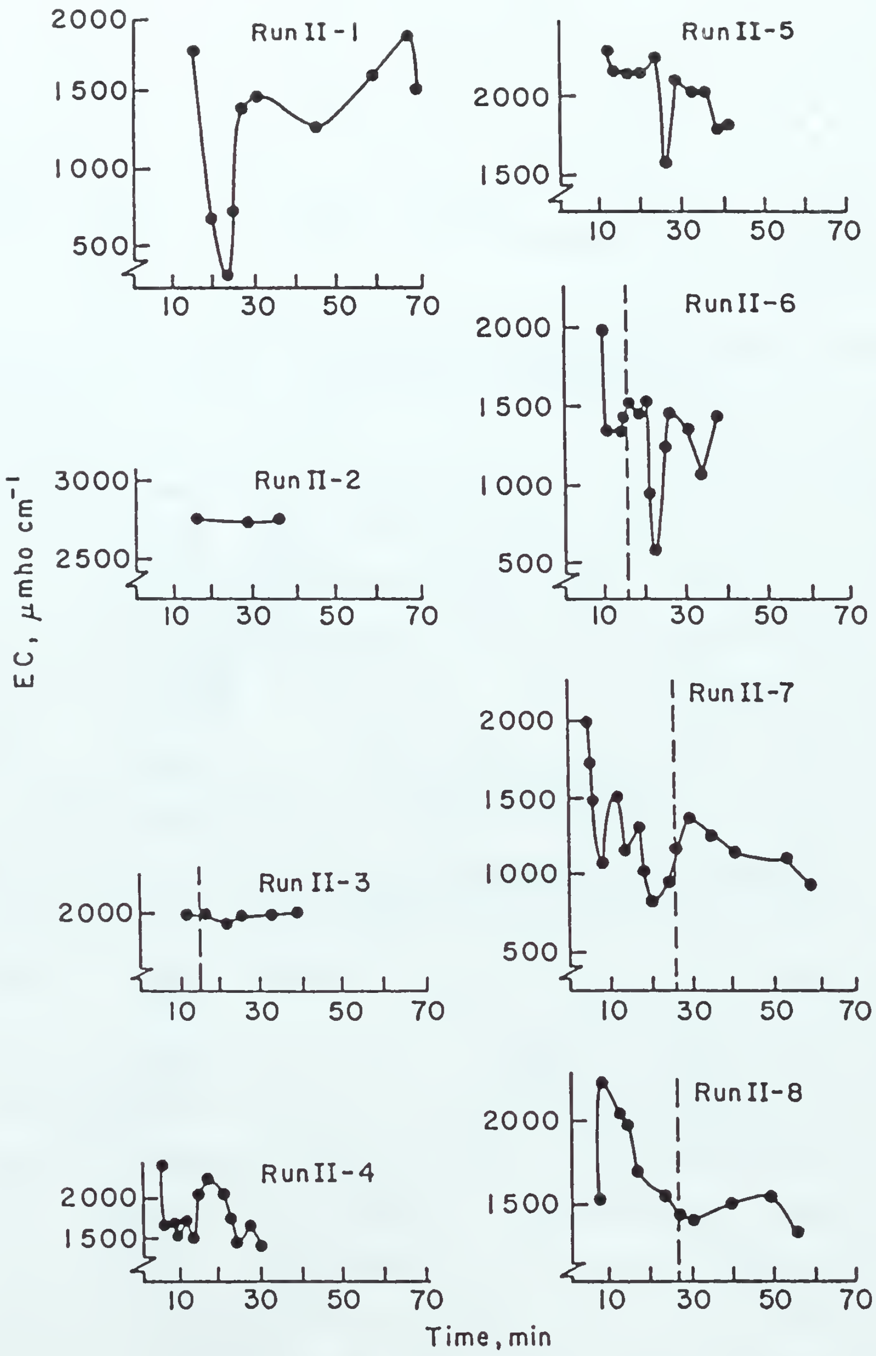
5-29 Temporal and spatial variations of salinity (EC) during direct runoff generation experiments of study I on plots I-9(A), I-5(b) and I-8(c). Vertical dashed lines indicate time of rill incision (b) or of rill formation (c) after Shen et al, 1981).

All stations exhibited an initial high EC. The smallest increase, about 25% (550 μmho/cm at Station A), occurred at the beginning of overland flow on the gentlest hillslope. EC continued to increase for a few minutes at all stations on Figures 5-29a-c or else it reached a maximum value for the leading edge of flow. Thereafter, EC decreased as a decay function. A second EC maximum appeared later in the run at several locations, most notably at all stations on plot I-8 (Fig. 5-29c).

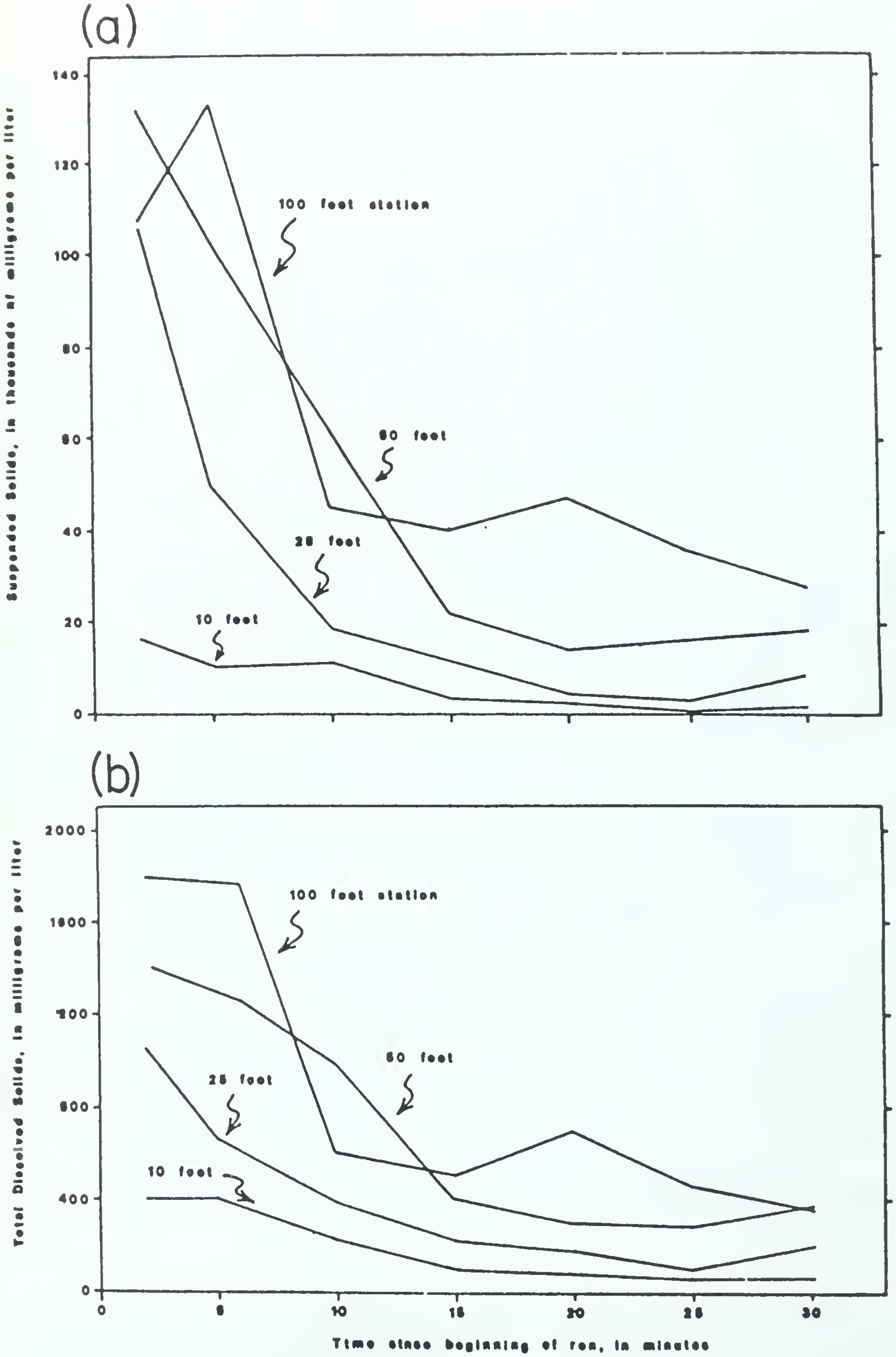
Figure 5-30 shows the temporal variation of EC from the onset of sprinkling for hillslope Study II. The runoff generated in these runs also exhibited high initial EC values. Similarly, the temporal trends of EC exhibited either one or two maxima. No distinct decrease in EC with time was noted during Runs II-2 and II-3 for which only few water samples were analyzed. Note that runoff was collected only at the bottom of the hillslope in this study, and that EC values were overall lower during sprinkling (Fig. 5-30) than during direct water application (Fig. 5-29).

The decrease of EC during the channel experiments (Fig. 5-31) of White (1977) were very similar to those depicted for the direct runoff generation experiments on hillslopes as well as during experiments undertaken by Achterberg (1981) in a flume (Fig. 5-32). The flume and the channel experiments all displayed initially high EC values that decrease with time (Figs. 5-31, 5-32).

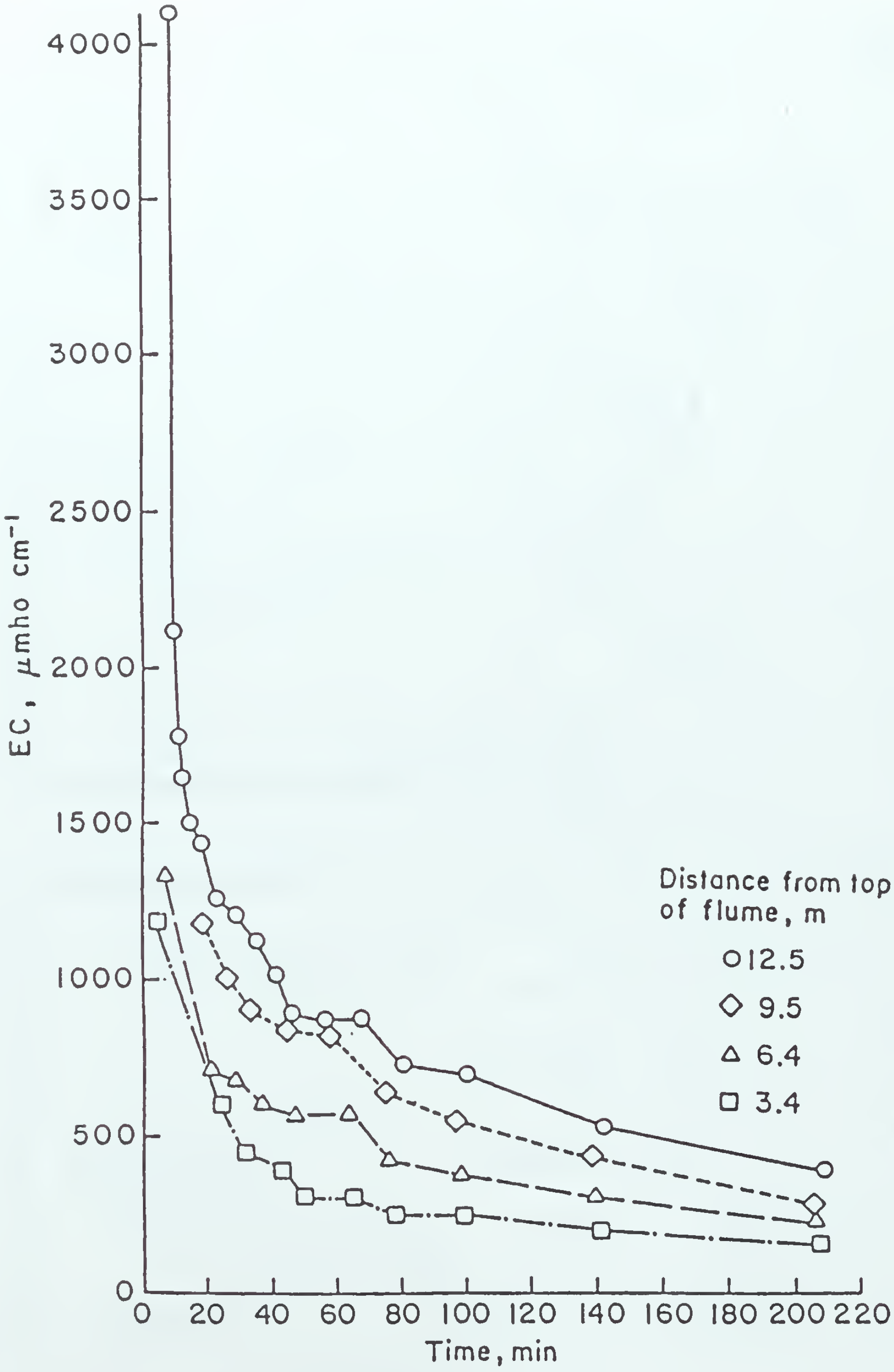
Spatial Variations of Salinity: The spatial variation of runoff salinity can be best understood if it is described with reference to the size of the contributing area in the following sequence: flume, entire hillslope segment, and channels. A down flume increase in salinity during direct runoff generation is illustrated in Figure 5-32. This trend also applies to overland flow on hillslopes, to rill flow (Fig. 5-29), and to channel flow (Fig. 5-31). An explanation of these trends is closely related to erosion by running water.



5-30 Temporal variations of salinity (EC), Hillslope Study II. Vertical dashed lines indicate time of initiation of rilling (after Shen et al, 1981).



5-31 Temporal and spatial variation of salinity (a) and sediment concentration (b) in channel 1-1, Run 1 (after White, 1977).



5-32 Temporal and spatial variation of runoff salinity (EC) during direct runoff generation in a flume (after Achterberg, 1981).

Sediment Transport and Salinity

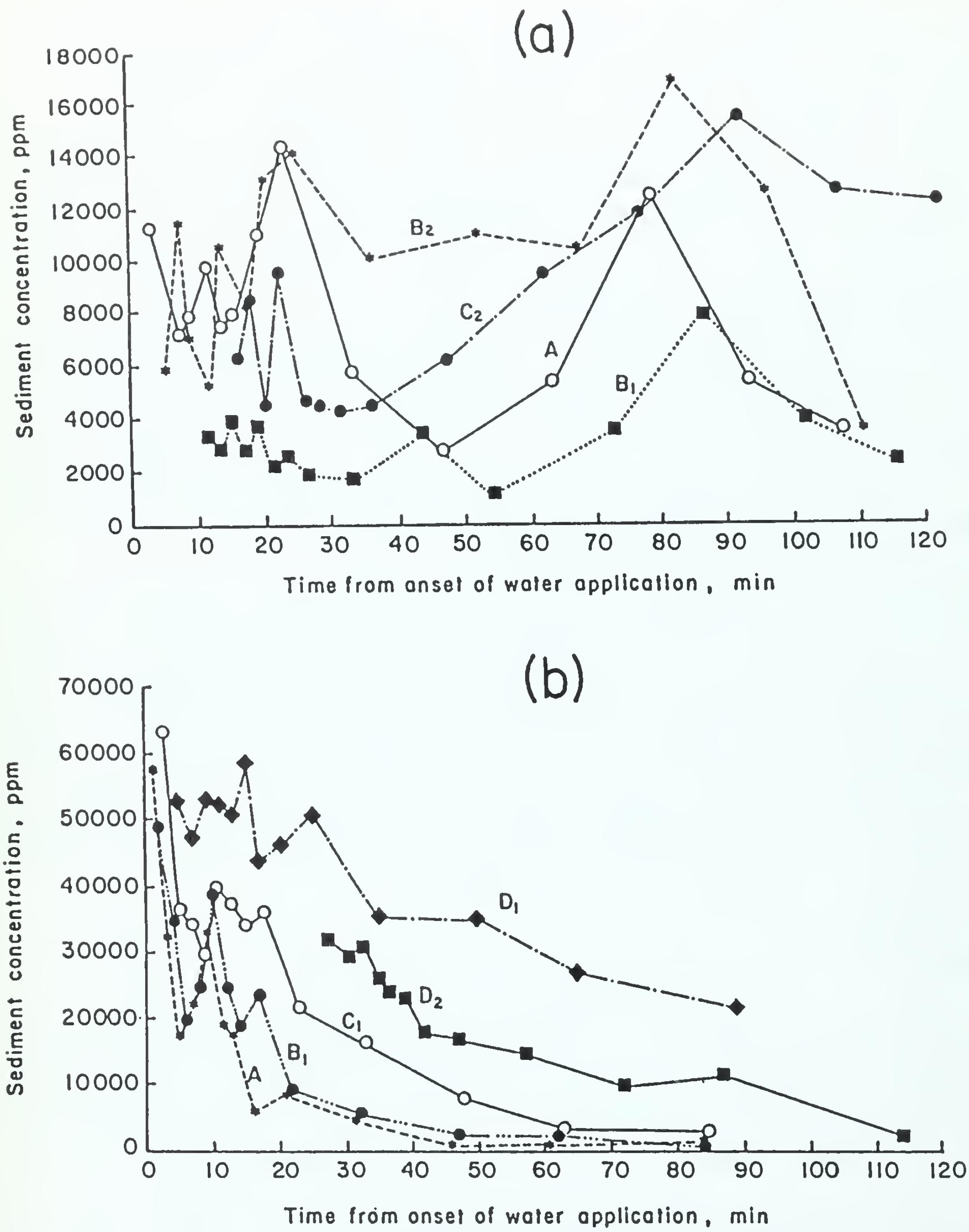
In the Mancos Shale terrain, the transport of sediment is closely linked to solute release. Analysis of data published as early as 1965 (Iorns, Hembree and Oakland, 1965) demonstrates that locations of high solute yields in the Upper Colorado River Basin are also those producing large yields of sediment. The Price and Dirty Devil Rivers are characterized by low water yields (0.66 and 0.58 percent, respectively) and by very high sediment yields (3.73 and 4.81 percent, respectively). It is particularly noticeable that the respective solute yields (2.79 and 2.28 percent) are also very high (Fig. 1-5). Similar high yields of both sediment and solutes occur in the central reach of the Gunnison Valley in the Delta-Montrose area of Colorado, throughout the Grand Valley, and in the San Juan River Basin between Shiprock, New Mexico, and Bluff, Utah. All these basins, valleys and reaches are extensively underlain by Mancos Shale. Mundorff (1972), Ponce (1975), Laronne (1977), White (1977), and Shen and others (1981) also demonstrated that solute release is related to sediment transport. Jackson et al (1984) have determined that salt release is 3.8% of sediment yield from three Badger Wash drainage basins.

Ponce (1975) showed that erodibility varies among stratigraphic members that outcrop in the Price River Basin (Table 5-6). With respect to Mancos Shale outcrops, the Mancos Undivided and the Middle and Lower Blue Gate members were associated with the highest sediment concentrations. These units are also the primary contributors of salinity in the basin. Linear correlation coefficients between EC and suspended sediment concentration exceeded 0.72 for 8 among 12 plots and were less than 0.53 only for 3 plots. These correlations indicate that variations in solute yield can be partly explained by variations in sediment yield for gentle Mancos Shale (<10 percent) hillslope source areas. White's (1977) data for channel flow substantiate this relationship.

Not only does total solute concentration correlate with sediment concentration, but temporal and spatial patterns are very similar on hillslopes (compare Fig. 5-29c with Fig. 5-33a and Fig. 5-29b with Fig.

Table 5.6. The Mean ($\overline{x}$) and the Standard Deviation (s) of the suspended sediment (S.S.) for the members of Mancos Shale. All values represent a composite average for plots one through six at each site.

Mancos Shale Member	Site	S.S. $\overline{x}$ (g/l)	S.S. s (g/l)
Musuk	1	2.32	0.70
Musuk	2	2.01	1.03
Musuk	3	--	--
Upper Blue Gate	4	2.47	1.14
Upper Blue Gate	5	5.29	3.00
Middle Blue Gate	6	6.13	3.24
Middle Blue Gate	7	7.77	3.73
Lower Blue Gate	8	6.98	0.97
Lower Blue Gate	9	7.06	2.13
Tununk	10	2.14	0.58
Tununk	11	1.48	0.83
Tununk	12	4.00	0.24
Undivided Mancos	13	3.71	0.44
Undivided Mancos	14	8.38	1.74
Undivided Mancos	15	9.30	1.69



5-33 Temporal and spatial variations of sediment concentration, plot I-8 (a) and plot I-5 (b) (Shen et al, 1981).

5-33a) and in channels (Fig. 5-31). It is particularly interesting that sediment concentration maxima occurred during erosion of the weathered surficial mantle at the onset of all experiments (a flushing effect), during rill formation (Fig. 5-29c at 75-90 min) or during rill entrenchment (Fig. 5-29b at 9-15 min). The downslope and downchannel increase in solute and sediment concentration may be identified in Figs. 5-29, 5-31 and 5-33. The spatial trend in solute concentration on hillslopes and channels is summarized in Fig. 5-34 for clarity.

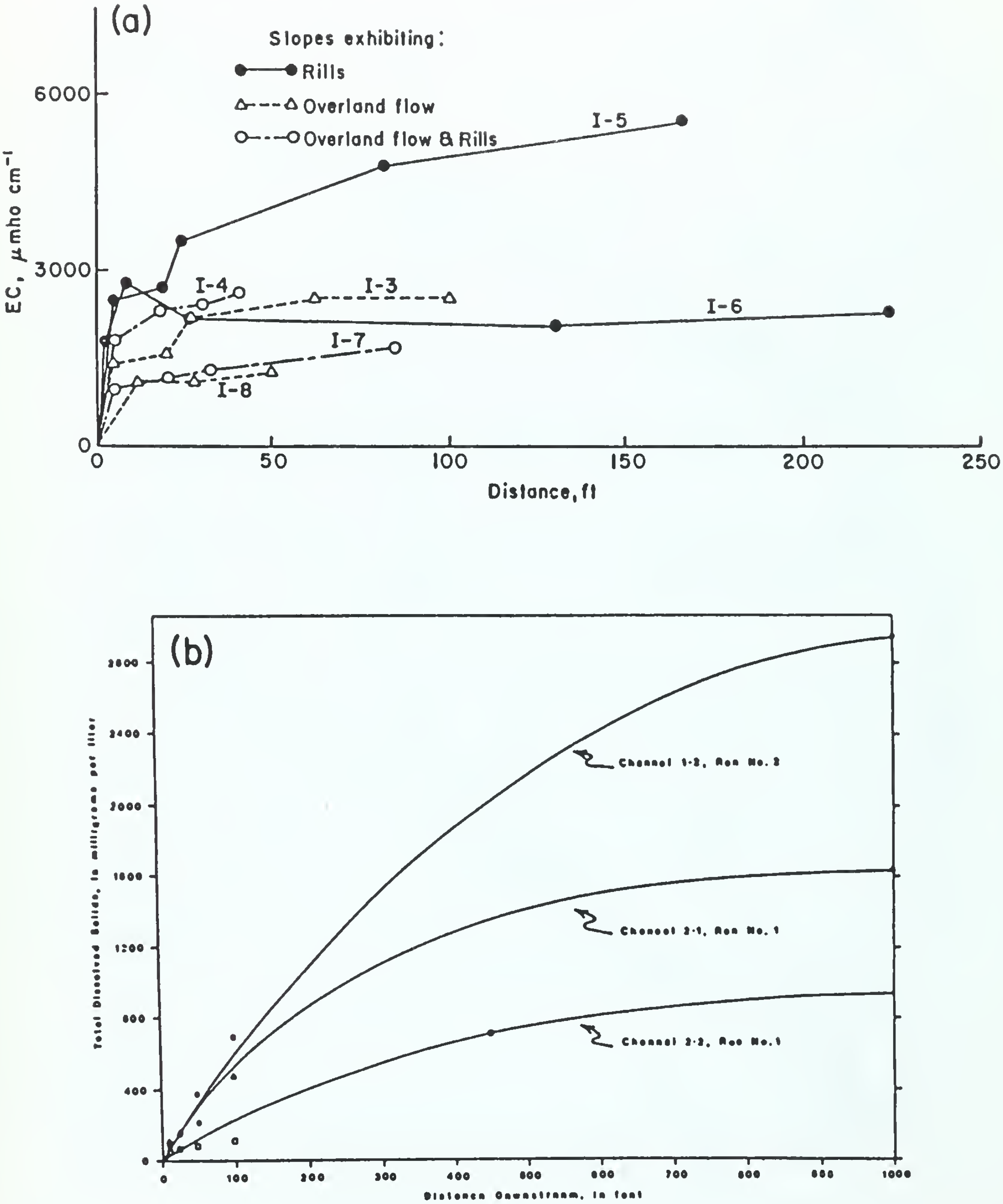
White's (1977) data show that solute concentration varies with sediment concentration nonlinearly downchannel (Fig. 5-35). Evidently, the supply of sediment affects this relationship. At the beginning of White's (1977) experiments sediment was available, and its concentration increased downchannel, but during later phases of each run sediment concentration changed less rapidly than salinity.

The downslope increase in EC is particularly noteworthy when comparing average EC of runoff for the two hillslope studies and White's experiments (Figs. 5-31 and 5-33). Both overland, rill and channel flow incorporated additional solutes with distance downslope and down channel due to 1) longer contact with dissolving minerals on the surface, 2) longer contact with transported sediment particles, and 3) increased concentration of sediment.

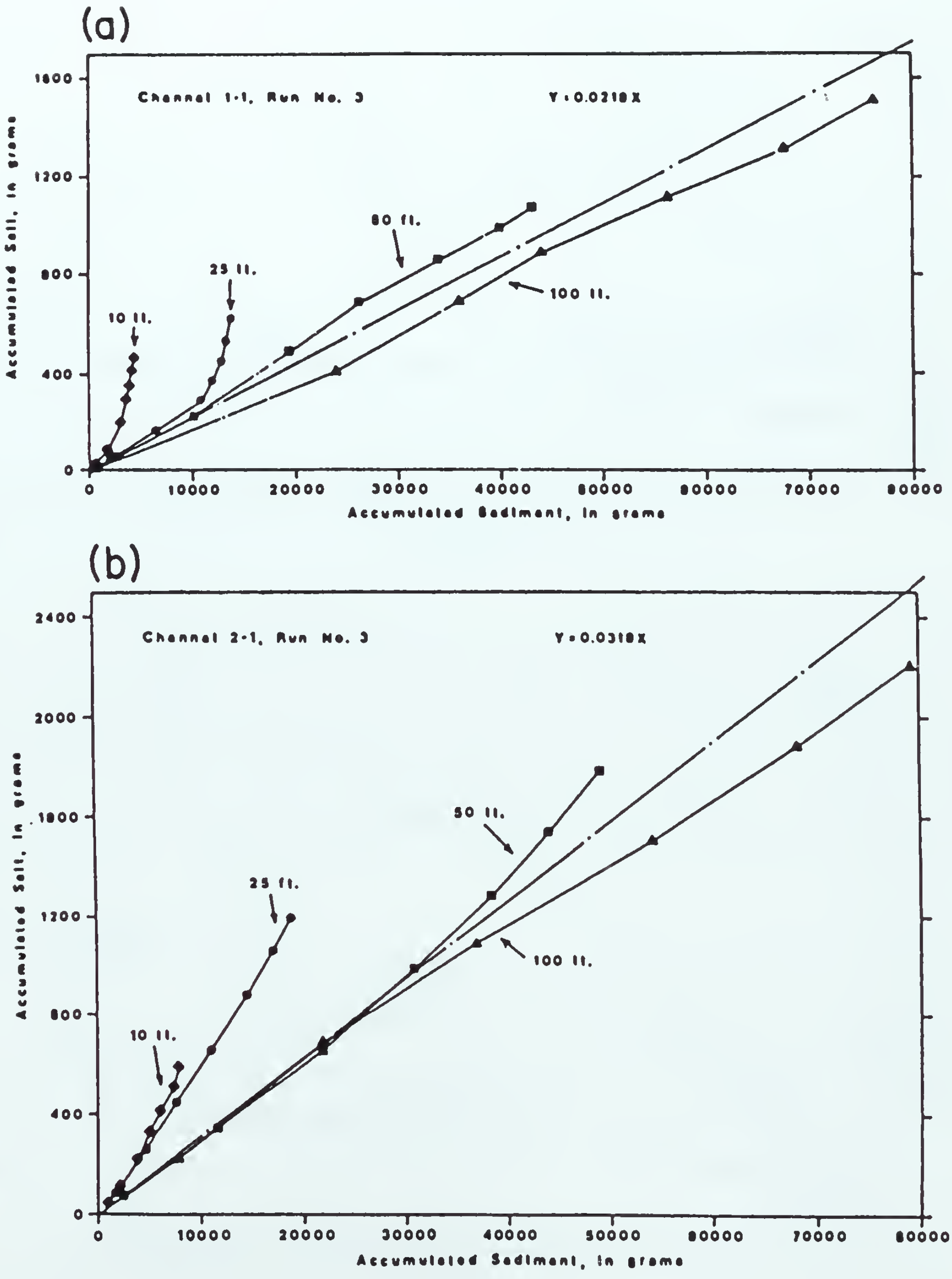
Flow Velocity

A most useful result of the Shen et al (1981) hillslope studies is the observed correlation ($r^2 = .80$) between the average EC of runoff on a given hillslope and its inclination (Fig. 5-36). This undoubtedly reflects the higher rates of erosion on steeper slopes.

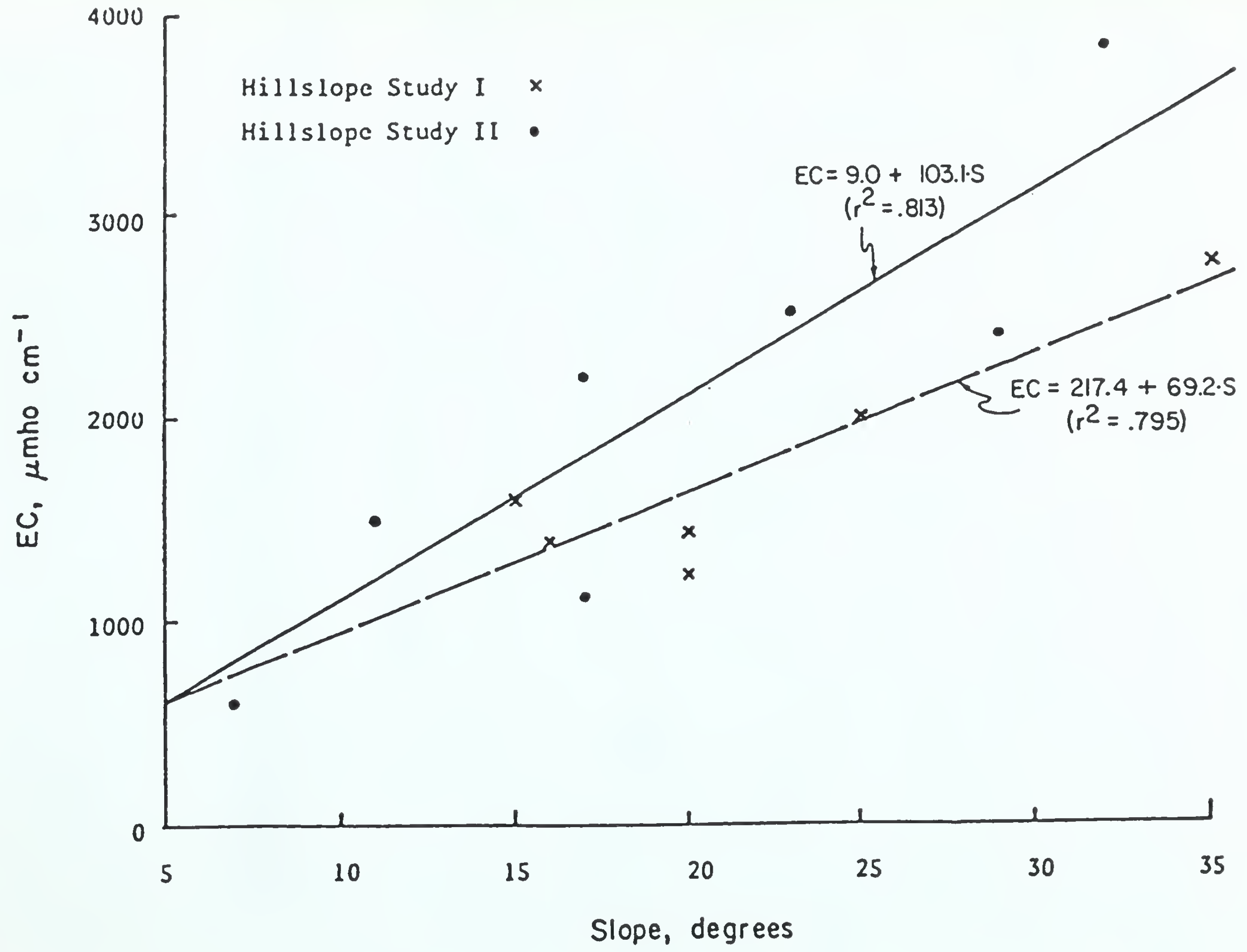
The variation of solute release rate with varying flow velocities was demonstrated in a laboratory experiment by Sunday (1979), and later by Nezafati, Bowles and Riley (1981). Both studies showed (Fig. 2-37) that the initial dissolution rate (as well as the final EC) increases with increase in flow velocity, an effect that was previously demonstrated, though indirectly, by Kemper, Olsen and deMoody (1975). Sunday summarized her results in a diagram (Fig. 5-38) which depicts the effects of both flow velocity and particle size on dissolution rate.



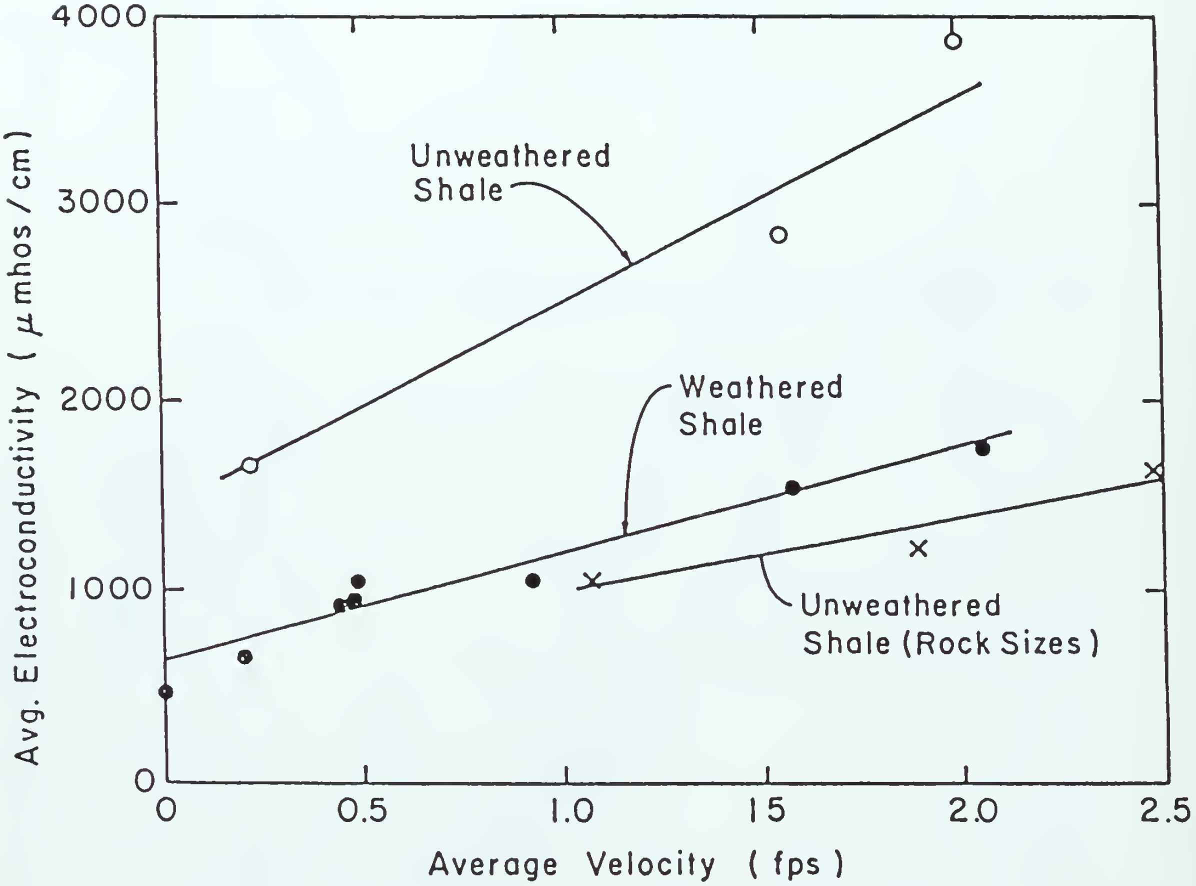
5-34 Downslope (a) and downchannel (b) variation of salinity in Hillslope Study I (from Shen et al, 1981) and in microchannels (after White, 1977).



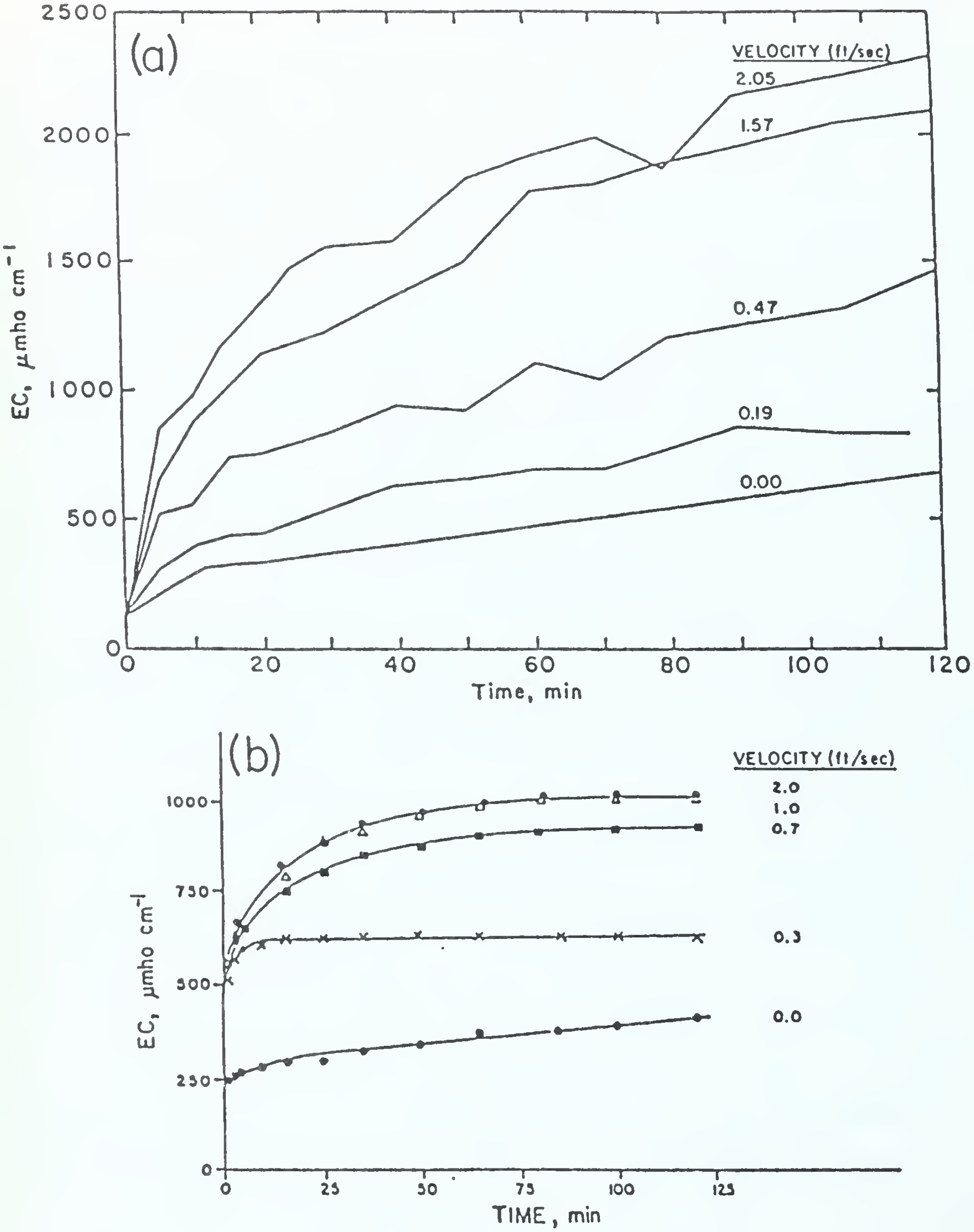
5-35 Accumulated salt versus accumulated sediment for channels 1-1 (a) and 2-1 (b), run 3 (after White, 1977).



5-36 Average EC versus hillslope inclination for Hillslope Studies I and II (after Shen et al, 1981).



5-37 Effect of flow velocity on dissolution rate of soluble minerals from Mancos Shale (a) (after Sunday, 1979) and from channel material (b) (after Nezupati, Bowles and Riley, 1981).



5-38 Variation of average EC (denoting dissolution rate when divided by the duration of the experiment) with average velocity. Note that dissolution rates are lower for coarse particles and for material with a lower SMC (weathered Mancos Shale) than those for 'unweathered', fresh samples of shale (after Sunday, 1979).

Sunday (1979) also demonstrated that the effect of turbulence on a soil-water mixture is, in fact, identical to increasing flow velocity.

In summary, a decrease of sediment concentration or flow velocity, and an increase in particle size and a decrease in the contact time between soil and water reduce the dissolution rate of minerals (specifically those that are soluble or moderately soluble) that are in sediments and soils.

The association of higher flow velocities, and increased rill erosion on the steeper hillslopes with higher flow salinities is indicated by the data in Figs. 5-28, 5-33 and 5-36. Given the assumption of a nonvarying soil cover (in terms of infiltration characteristics, erodibility, SMC and mineralogy of soluble minerals), as hillslope gradient increases so does the power available for sediment erosion and transport. Solute release will increase, as more sediment is entrained and transported by the flow.

Not only does erosion increase with slope inclination but it increases sharply when rilling takes place. This explains the positive correlation between solute concentration and slope inclination, flow velocity and rilling.

The EC vs. time curves generally consist of an initial maximum, followed by a decrease. The initial maximum may be explained as a surface flushing effect. Highly erodible weathered particles and accumulations of soluble minerals account for the maximum, which may be seen by comparing the temporal variation of sediment concentration (Fig. 5-33 and 5-31a) with the EC vs. time curves (Fig. 5-29 and 5-31b, respectively). Note the contemporaneous increase in both EC and sediment concentration for these hillslopes. These observations agree with the high correlation found by Ponce (1975) between EC and sediment concentration. The statistical correlation between sediment concentration and EC is further manifested in run I-8 (Figs. 5-29 and 5-33a) where rill development late in the run accounts for the increase in both sediment concentration and EC.

Summary

Perhaps the most important conclusion to be drawn from this study is that the geomorphic and hydrologic characteristics of Mancos Shale hillslopes and drainage basins are determined by seasonal changes in soil characteristics on slopes. The loosening of the soil surface on the slopes by frost action has a pronounced effect on (1) erosion process (creep is important during winter and spring), (2) infiltration capacity (the soil surface is most permeable during winter and spring), and (3) runoff (average runoff and the ratio of runoff to precipitation are relatively low in the spring).

The compaction of the permeable surface by rain-beat after frost action has a pronounced effect on (1) erosion process (erosion by rills and rainwash are important during summer and fall), (2) infiltration capacity (the soil surface is least permeable during summer and fall), and (3) runoff (average runoff and the ratio of runoff to precipitation are greatest in the late summer and fall).

The studies in Badger Wash and Montrose may provide a misleading picture of the erosional characteristics of the Mancos Shale terrain. This is because the measurements were concentrated on relatively steep and bare badland slopes. However most of the other studies on the Mancos Shale appear to be biased toward flatter pediment-type surfaces as exemplified by the studies of Ponce (1975) and Simons and others (1982).

The field and experimental studies demonstrate conclusively that erosion rates are greatest on steeper slopes. As salt production is closely related to sediment concentration, it is apparent that both high sediment and salt production will occur in steep terrain (Johnson's badlands, Chapter 3) whereas significantly less sediment and salt will be produced from pediments and alluvial valley floors unless they are being dissected.

6) EROSION CONTROL MEASURES

Previous research into the mechanisms of salt dissolution and transport implies that there is a relationship between suspended sediment load and total dissolved solids in streams and rivers (see Shen et al, 1981, Hawkins, et al, 1977). Therefore, a reduction of sediment discharge should bring about a reduction of salinity. Such an approach would be most efficiently applied to those areas experiencing active erosion of the most saline materials within the Mancos Shale terrain. Two general approaches can be followed to reduce the sediment yield of a watershed. Hillslope and lower-order stream channel erosion can be reduced to prevent sediment from reaching higher order stream channels, or impoundment structures can be placed at the outlet of a watershed to trap all incoming sediment. Both approaches have advantages and disadvantages and the application of one or the other approach should be evaluated on a case by case basis. For a more in-depth summary of erosion control techniques and their relative success see U.S. Bureau of Land Management (1978).

Hillslope Erosion Control

Maintaining sediment on-site is a direct means of reducing sediment yields and salt loads from watersheds underlain by saline materials. A number of surface treatments have been used by government agencies on western rangelands. The techniques applied include contour furrows, pitting, ripping, terracing, chaining, conversion to grass cover, and grazing management. Most of these practices were applied to reduce erosion and sediment yield, however, chaining and conversion of vegetation to grass cover were implemented to increase water yield. An evaluation of the success of erosion control practices on rangeland by Branson et al (1972, p. 149) states that "failures have been surprisingly frequent". In New Mexico, for instance, up to one-half of the structures built for sediment control have been breached (Branson et al, 1972).

Success of the various land treatments is highly variable except for contour furrowing and intensive grazing management, both of which consistently reduce sediment yield and runoff. In some cases replacement of sagebrush with grass produced a decrease in sediment yield and an increase in runoff (U.S. Bureau of Land Management, 1978), which should produce an especially large reduction of salt due to a reduction of the amount of saline suspended sediment. Other surface treatments (pitting, ripping, chaining) were not found to have distinctly positive or negative impacts on runoff and sediment yield.

Contour furrowing reduces runoff by ponding water between ridges of soil constructed along the contour of a slope. Both water and sediment are trapped by the ridges and the depressions between ridges are filled with sediment which reduces the effectiveness of the treatment with time. The lifetime of contour furrows is estimated to be up to 15 years (less in highly erosive areas) at which time retreatment is necessary to continue erosion control (U.S. Bureau of Land Management, 1978). The effects of repeated disturbance of vegetation and soil surface on vegetation density and soil structure are not known. Use of contour furrows is not suggested on slopes greater than 10 percent, and thus, the procedure cannot be used in steep badland areas of Mancos Shale where saline sediment production is highest.

Studies at Badger Wash (Lusby et al, 1963; Lusby et al, 1971; Schumm and Lusby, 1963; Schumm, 1964; Lusby, 1979) demonstrate that there was a reduction of runoff and sediment yield from Mancos Shale basins when comparing grazed and ungrazed basins. An important finding was the seasonal change of infiltration rates and soil properties. During the spring the soil surface is loose which permits increased infiltration, and therefore, decreases runoff and sediment yield. Throughout the summer and fall the soil becomes more compacted, thereby reducing infiltration and increasing runoff and sediment yield. Grazing during the late winter and spring, when the soil surface is fragile and easily compacted by the tracking of sheep or cattle, causes a significant decrease in infiltration and subsequent increase in runoff and sediment yield. Although salinity of runoff was not measured during the Badger Wash studies, Jackson et al, (1984) found that about 4% of the eroded material is salt. Reduction of grazing during the spring, when the soil surface is more susceptible to damage will reduce salinity and runoff from these areas. This conclusion, however, is restricted to high sediment producing areas such as the Badger Wash drainage basins that have steep slopes (Fig. 5-19), moderately saline-soils, and 8-15 percent vegetative cover.

Channel Erosion Control

Sediment which is removed from hillslopes will enter the channel network of the drainage basin, and it will be transported downstream as dissolved load, suspended load, or bed load. Additional sediment may be obtained from channel bed and bank erosion, which may occur at minor rates along the length of a channel system or at accelerated rates where the channel is incised. As suspended load and bed load increase and as the mixing time between water and sediment increases, the dissolved load (salinity) will increase. Salinity can, therefore, be reduced by minimizing channel erosion, especially in areas of accelerated erosion such as gullies.

Water spreading is a technique that is used to reduce channel erosion as well as downstream runoff and sediment yield. Water is diverted out of a channel onto the adjacent flood plain or other relatively flat area by dike systems which are constructed both to divert flow laterally from a channel and to retain water and sediment for consumptive use by plants. Spreader systems should be designed for extremely large flows (Gifford, 1972) but they should not be used in areas of high sediment yield, and they should not be constructed on slopes greater than five percent. The spreader systems are expensive and complex to build and they may also increase the salinity of subsoils (U.S. Bureau of Land Management, 1978). Even if water spreaders are effective in controlling salinity, the deposited sediment and its contained salts must be protected from further erosion.

Gully plugs or small grade-control structures are a means of stabilizing channels at points of accelerated erosion. Sediment is trapped behind these structures, and it will also be deposited in the backwater upstream of the structure (Lusby and Hadley, 1967). Heede (1970, 1975) distinguishes between continuous and discontinuous gullies and points out that treatment will be different for the two types of gullies. Continuous gullies are best treated with a structure at the mouth of the gully whereas discontinuous gullies should be treated at the nickpoint at the head of the gully. Grade control structures or gully plugs must be constructed properly to withstand the forces of extreme flows (U.S. Bureau of Land Management, 1978).

Gully plugs must be impermeable in order to serve as effective salinity control measures (U.S. Bureau of Land Management, 1978). Efflorescent crusts in channels downstream of stock ponds indicate that seepage beneath an impoundment structure returns salts to the surface water system. An impermeable barrier under deposited sediment is necessary to make gully plugs completely successful.

Retention dams will trap almost all sediment from the upstream watershed as well as most of the water. As with gully plugs it is important that the reservoir behind the dam be impermeable for the structure to control salinity (U.S. Bureau of Land Management, 1978). Retention dams rapidly fill with sediment in areas of high sediment yield thereby greatly increasing the danger of damage to the structure by over topping, as well as eliminating the storage capacity of the structure. From a geomorphic perspective, however, even a filled retention dam and reservoir will reduce upstream erosion by raising the baselevel of the channel. However, the potential for dam failures raises serious questions about the long-term success and safety of using retention dams to control salinity.

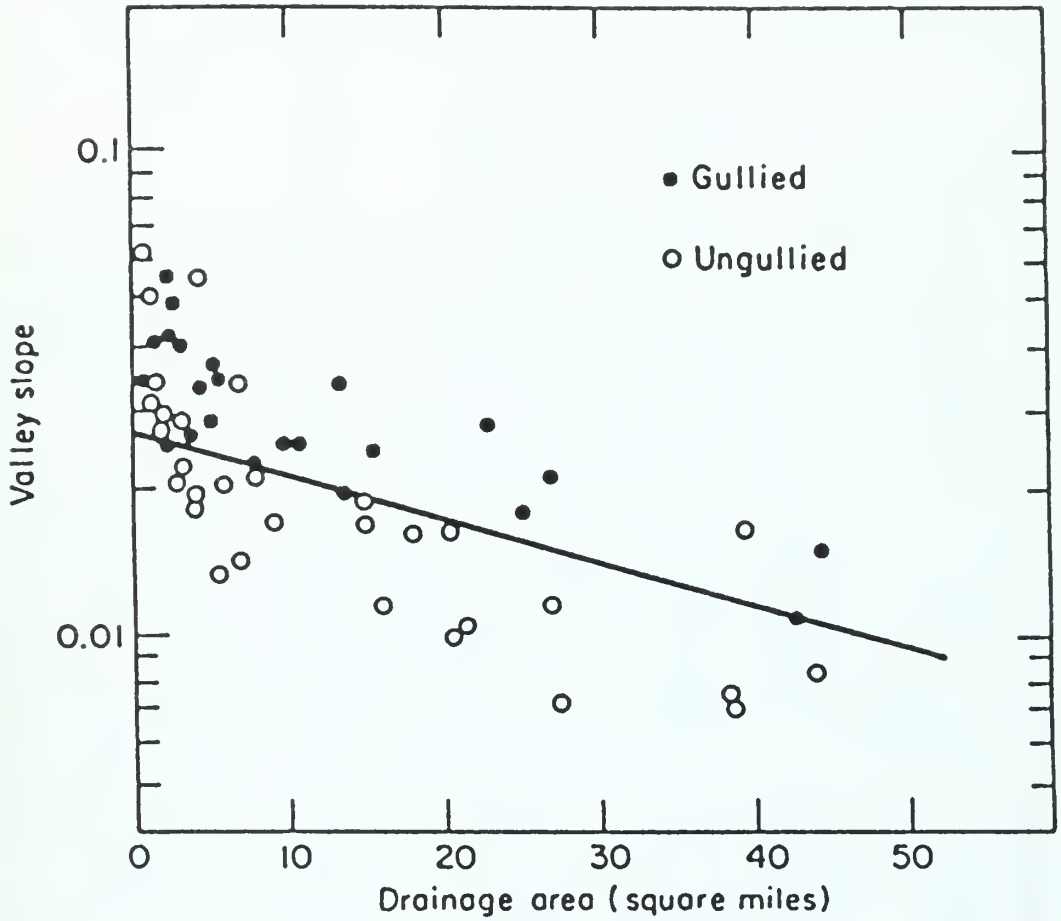
Geomorphic Approach

A geomorphologist views the landscape as a system composed of hillslopes and a network of channels which has developed in response to the interaction of erosional forces and the materials at the land surface. Areas viewed as serious problems by land managers and engineers because of high rates of erosion are seen as parts of a larger system by a geomorphlogist. This broader perspective provides insight into the functioning of the system and, therefore, insight into how and where to treat the problem. Erosion is a process to be understood in the system context in order that existing land management and engineering erosion control techniques may be most efficiently applied

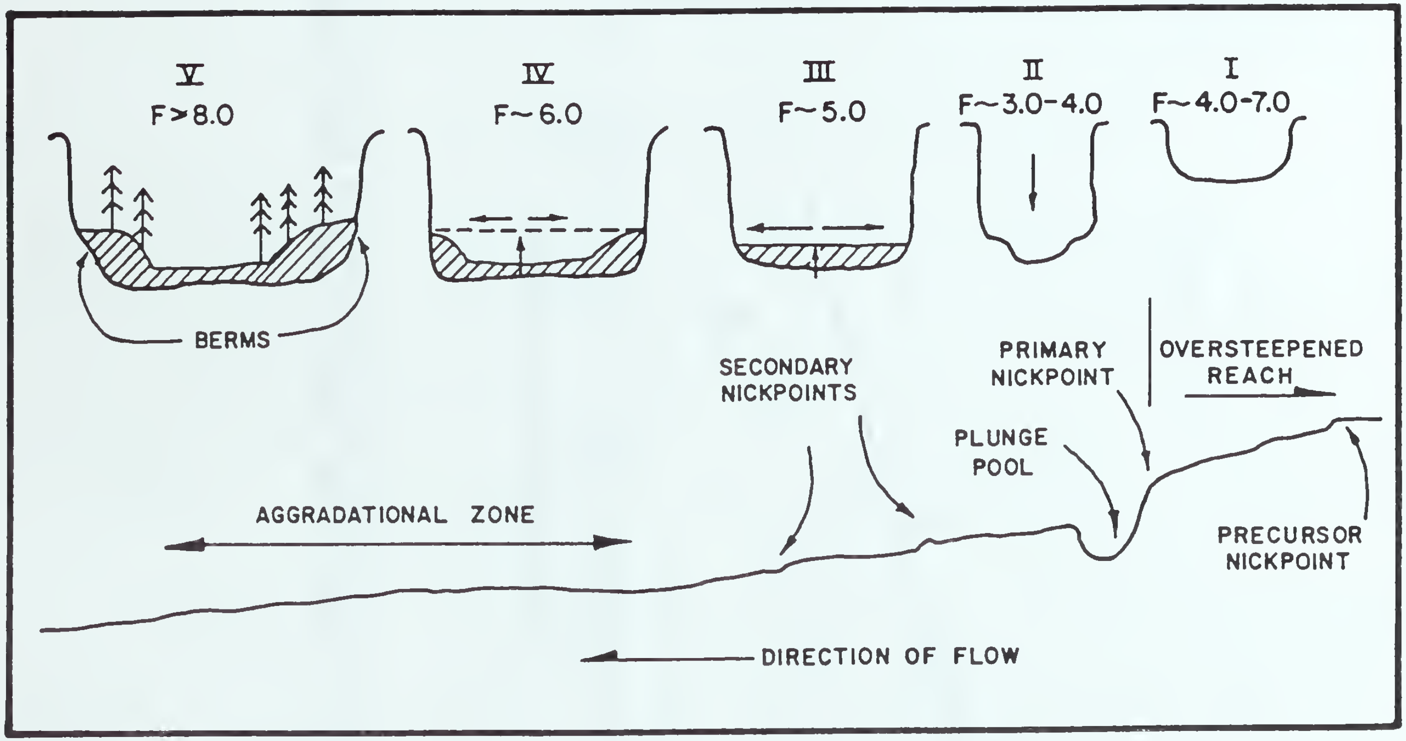
(Schumm, 1969). For example, discontinuous gullies have formed on some valley floors of the Piceance Creek basin in northwestern Colorado. Valley-floor slope and drainage areas were determined for both gullied and ungullied valley floors in the basin. A plot of valley-floor slope versus drainage area (Fig. 6-1) reveals a threshold valley slope above which valley floors are unstable (Patton and Schumm, 1975). The identification of the threshold enables land managers and engineers to locate areas of incipient instability near the threshold line where erosion control procedures will be most effective in preventing gullying. Areas which plot well below the line need little or no erosion control, whereas valley floors which plot above the line and which are gullied are best treated with engineered structures at nickpoints where erosion is most active. A reanalysis of the Piceance Creek data (Begin and Schumm, 1979) and a similar study in northeastern Colorado (Schumm et al, 1984) indicate that rather than a threshold line, there is a threshold zone within which both gullied and ungullied valley floors are located. Above the zone all valley floors are incised and below it none are incised.

Once a gully has developed or a stream channel has started to incise, the channel will stabilize naturally after passing through a series of stages which produce a stable channel. Studies of incised channels in northern Mississippi (Schumm et al, 1984) revealed a cycle of channel evolution resulting in a stable incised channel (Fig. 6-2). The history of an incised channel is incision, widening, aggradation and the develop ment of a new "stable" channel.

Identification of the stages of landform adjustment will aid in placing erosion control structures. For instance, a type IV channel (Fig. 6-2) will evolve naturally into a relatively stable type V channel and therefore, it may not require erosion-control treatment. However, a type I or II channel is just beginning the cycle of channel incision and, therefore, the greatest benefit will be realized from application of erosion control techniques to these channel types. However, erosion control will be most difficult to apply to these channel types because the greatest change can be expected in these reaches. Geomorphologic studies can provide a tool to aid in the evaluation of the need for an



6-1 Relation between valley-floor slope and drainage area for small drainage basins, Piceance Creek area, Colorado (from Patton and Schumm, 1975).



6-2 Schematic longitudinal profile of an active channel showing identifiable features. Schematic cross section profiles corresponding to reaches on the longitudinal profile show the evolution of the reaches from Type I to Type V. Typical width-depth (F) values are shown. Size of the arrows indicate the relative importance and direction of the dominant processes, degradation, aggradation and lateral bank erosion.

erosion control project. In addition, the timing of the installation and its location are critical and this type of information can be provided by geomorphic studies (Schumm, et al, 1984; Van Haveren and Jackson, 1986).

Summary

It is an unavoidable fact that erosion will occur where there is topographic relief and running water. Entire mountain ranges have been leveled by erosion in the geologic past and the forces of erosion are the same now as then. Attempts to control salinity by erosion control can at best only slow the process or store sediment temporarily (at least in terms of geologic time).

Grazing control can produce a reduction in sediment yield and runoff simply through elimination of any disturbance of the natural system when it is in the most fragile stage of the seasonal cycle. Treatment would consist of removal of the cause of the disturbance during late winter and spring. Further efforts to retain sediment on hillslopes by contour furrowing require a disturbance of the system to produce results. Although there are clear reductions in sediment yield and runoff with this erosion control method, the possibility of detrimental impacts due to creation of the contour furrow system are unknown (U.S. Bureau of Land Management, 1978). Contour furrowing may not be applicable to high sediment producing areas since it is recommended for slopes less than ten percent.

Treatment of gullies has been reasonably successful when control structures are built properly, but check dams and gully plugs do not retain salts. Construction of retention dams, although highly successful in trapping sediment (and dissolved solids, if seepage is prevented) causes a significant disturbance in the continuity of water and sediment discharge. Clear water released from a dam will cause increased erosion in the channel downstream of the dam. The trapped saline sediment must be permanently protected where it is deposited behind the dam or removed to another permanent disposal site.

Erosion control methods cause varying degrees of disturbance of the watershed. Those with the most disturbance may be simple to apply yet may derive the least reduction in salt loading (pitting, contour furrows etc.). Those methods with the least disturbance (gully plugs, retention dams) may be expensive and difficult to apply, but they may result in greater reduction in salt loading. Analysis of the impacts on the geomorphic system will aid in determining the most efficient system for reducing diffuse-source salinity.

7) CONCLUSIONS AND RESEARCH NEEDS

The salinity of the Colorado River is the result of a complex set of processes, both natural and man-induced. An understanding of the processes which increase the salinity of the river is necessary in order to determine methods and procedures that will be effective for reducing salt loading at Imperial Dam. Obviously, the cost of various measures must be weighed against the benefits in terms of reduced damage due to salinity. This will provide a measure of the economic effectiveness of a particular salt-reduction technique.

It was demonstrated in Chapter 5 that salinity of runoff is related to the suspended-sediment load of the flow. In other words, where sediment yield from watersheds underlain by saline geologic formations is high, the total dissolved load or salinity will also be high. Reduction of either runoff or erosion from these areas will reduce salt loading of the Colorado River. Therefore, identification of areas of high sediment yield is an important step in determining where erosion control measures will be most effective for the reduction of salt contributions from the large area of Mancos Shale within the Upper Colorado River Basin.

The soluble mineral content SMC of Mancos shale is variable, as are the landforms that have developed on it. Therefore, local studies, although providing important data, cannot be used to interpret the morphology, and sediment and salt production from all of the Mancos-Shale terrain. In fact, this report deals only with Mancos-Shale terrain of the low-elevation drylands between Grand Junction, Colorado and Price, Utah, although, the Mancos Shale and similar saline shales are found throughout the Upper Colorado River Basin.

The studies in the Badger Wash area emphasized hillslope erosion and sediment yields from badlands. These studies indicated that erosion is rapid and that it produces large amounts of sediment; therefore, surface runoff and erosion from the Mancos Shale are major contributors of dissolved solids to the Colorado River.

The Utah State University group, on the other hand, conclude that surface erosion is not a significant contributor of salt to the Price

River in the western area. For example, Riley et al (1982), concluded that the primary source of salinity in perennial streams is saline groundwater inflow. This is expected where runoff is perennial, but the conclusion is based on results obtained when flow was produced artificially for time periods of 4 and 7 hours in a small ephemeral-stream channel. TDS decreased significantly, with time, as stored salts were flushed from the channel, but the low TDS following flushing does not demonstrate that after one flow event TDS will remain low because runoff from overload flow was absent. Bowles et al (1982) also concluded that surface sources produce only a small part of total salt loading. They studied effloresence salts in a reach of Bitter Creek, and they concluded that 7.5% of the salt passing the Woodside Utah station is derived from this source. However, the origin of the salts that effloresence could be overland flow. Therefore, this 7.5% of the total salt load may actually originate from bedrock and soil erosion outside of the channel. Bowles et al (1982) used these data on efflorescent salts plus other information from the Coal Creek watershed to conclude that only 0.5% of the total salt load at the Woodside, Utah gaging station is contributed from erosion of upland areas and that the greater part of the salt delivery is from ground water. However, Riley et al (1982) state that the Coal Creek basin contains no saline soils, and it has been contour furrowed, both of which will greatly reduce salinity of surface flows. This is a very different type of watershed, as compared to those investigated in the eastern study area.

Riley et al (1982a) summarize the conclusions of the Utah State University group for the Price River basin. The conclusions from 5 separate investigations are that salt from overland flow and from small channels range from 0.84% to 11.95% of the annual salt load at Woodside, Utah. They further report on a study in 7 small watersheds in the Price River basin, where runoff was measured for a short period. The seven basins were small with slopes ranging from 5% to 19% and saline soils constituting from 0% to 34% of the watershed. Among their conclusions the following are relevant to this review:

1) There is great varability of suspended sediment and TDS due to watershed variability and to the distribution of saline soils.

2) Salt yields are enhanced with time between runoff events.

3) Slope has little effect on runoff, suspended sediment or TDS.

4) The ratio of saline-soils area to watershed area has a direct effect on salinity levels.

Conclusion 3 is in marked contrast to the findings elsewhere. The lack of the expected relation, an increase of sediment load and salinity with slope, probably is due to the small range of slopes studied (5% to 19%) and to the great range of saline soils found within the watersheds (0% to 34%).

The conclusions from the western (Price) and eastern (Badger Wash) areas appear to be inconsistent, however the disparate results may be due to differences in topography and soils between the areas. The western-area studies appear to have been carried out in areas of gentle slope with less saline soils than in the eastern area. In addition, substantial areas near Price are pediment remnants that have been shown to be relatively stable landforms (Johnson, 1982). In contrast, the eastern study areas are characterized by steep drainage basins and hillslopes that are eroded into Mancos Shale bedrock. Soils are thin and saline except on the pediments.

The first step in the evaluation of the Mancos-Shale terrain, as a diffuse-source of salinity, is to obtain an adequate representation of landform types and distribution in the Upper Colorado River Basin. Expansion of Johnson's (1982) landform map of the Book Cliffs area between Grand Junction, Colorado and the Utah state line to cover areas in the Upper Basin that are underlain by saline geologic formations would provide the first complete evaluation of high sediment and high salt producing areas. The "badland" map unit, as used by Johnson (1982), was identified as a major sediment and salt producing landform, whereas pediments were identified as being relatively stable. Alluvial valley floors, depending on channel incision, can be relatively stable or very unstable. Integration of a landform map with geologic and water quality information will help in the identification of areas where erosion control could be effective in reducing salinity of runoff.

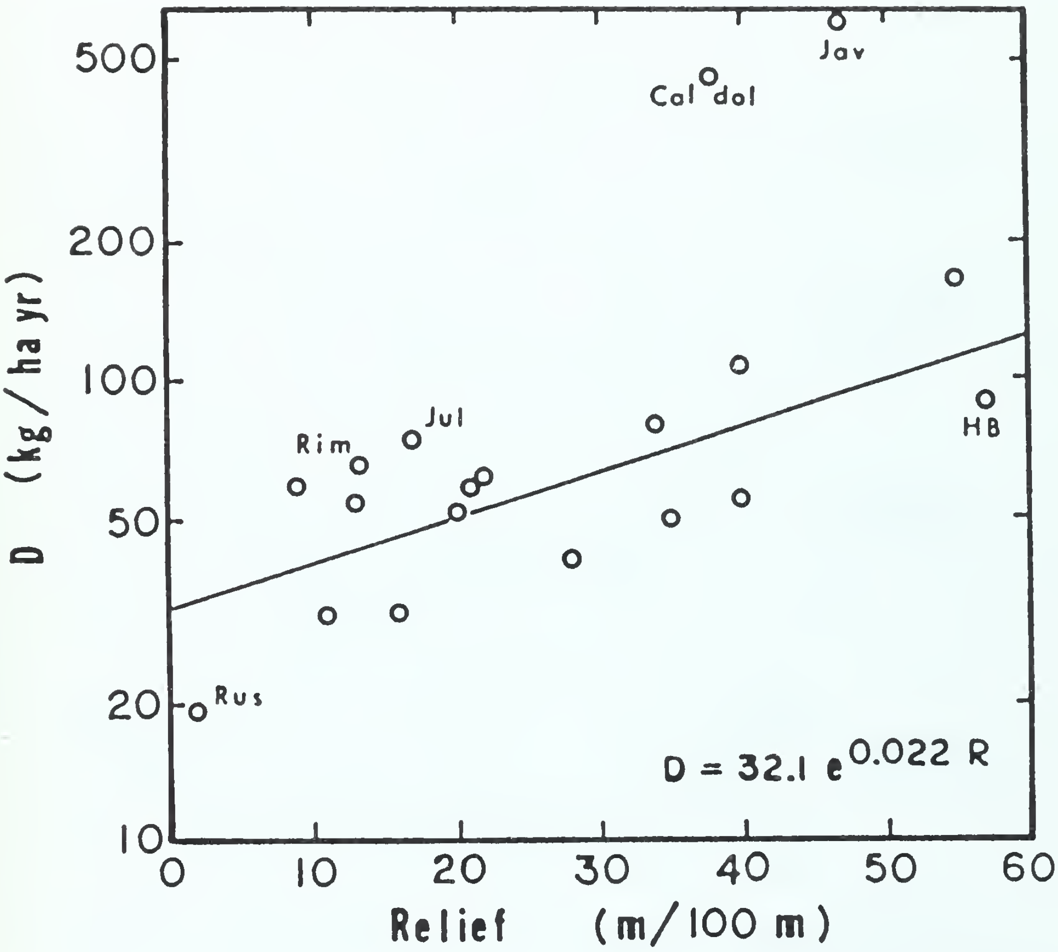
Total dissolved load of runoff has been found to be directly related to hillslope inclination or relief (Shen et al, 1981; Alexander, 1985)

(Fig. 7-1). Badlands, which have steep slopes and high relief, will produce more dissolved material or salinity than landforms with gentle slopes and low relief. In addition, some badlands are underlain by different lithologic materials which may affect the salinity of runoff. For instance, Johnson (1982) noted that units within the Mancos Shale that consist of interbedded shale and sandstone had a lower SMC than areas underlain predominantly by shale. Runoff from drainage basins on the interbedded shale and sandstone will have lower salinity than runoff from shale basins despite the fact that both basins may be classified as badlands. The landform maps, therefore, should identify specific areas or drainage basins with a high potential for sediment production.

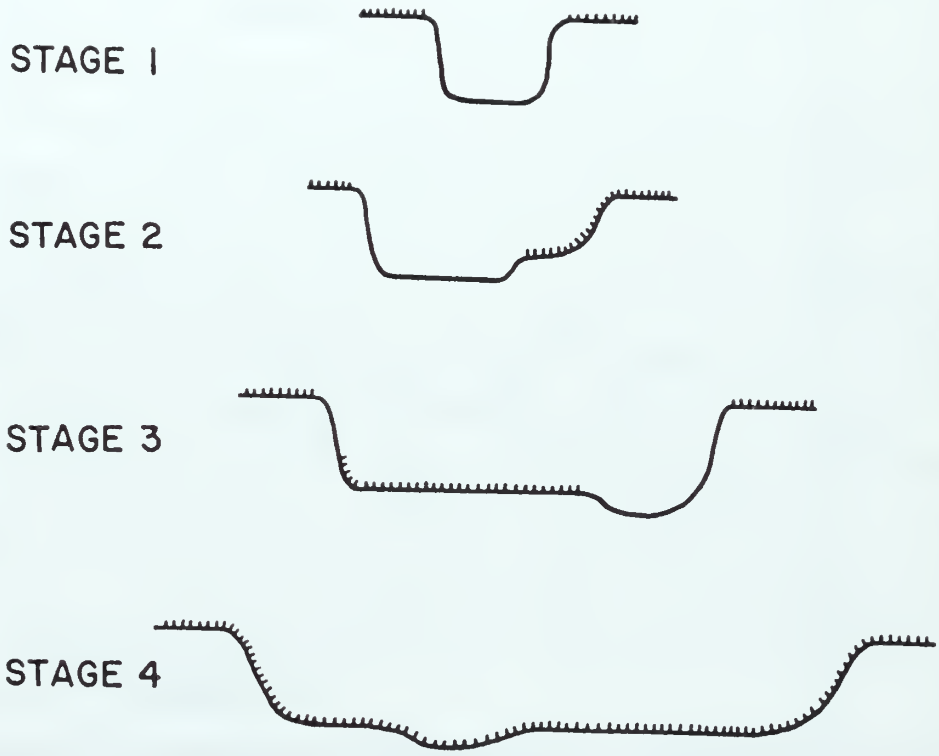
In addition to the slope criterion for the identification of high sediment producing areas, the presence of incised channels will also be an indication of high sediment and salt production. Within the eastern area most channels are incised, but elsewhere in the large outcrop area of the Mancos Shale there should be valley floors that are not incised. A relation similar to that of Fig. 6-1 could be developed for the Mancos-Shale terrain that would permit the identification of threshold conditions at which a channel or a valley floor is unstable. If this could be done it would be extremely valuable not only for salinity concerns, but also for providing a basis for preventive conservation on the Mancos-Shale terrain.

Geomorphic insight may also be important in determining the location of erosion control structures in a gully. For instance, a structure placed at a nickpoint, where erosion is actively creating a headcut, will be most effective in retarding gully erosion. Heede (1970, 1975) points out that continuous and discontinuous gullies require different treatment in terms of the location of control structures. Certainly structures are not required where the channel is in an aggradational or healing mode.

Time is an important variable in the development of a gully. In the Republic of South Africa four distinct stages in the evolution of a gully were identified (Fig. 7-2) (see also Schumm et al, 1984; and Harvey et al, 1985). The initial incision produces a narrow deep channel, and during subsequent stages the channel deepens, and then



7-1 Relation of chemical dendation (D) to relief of small watersheds (from Alexander, 1985).

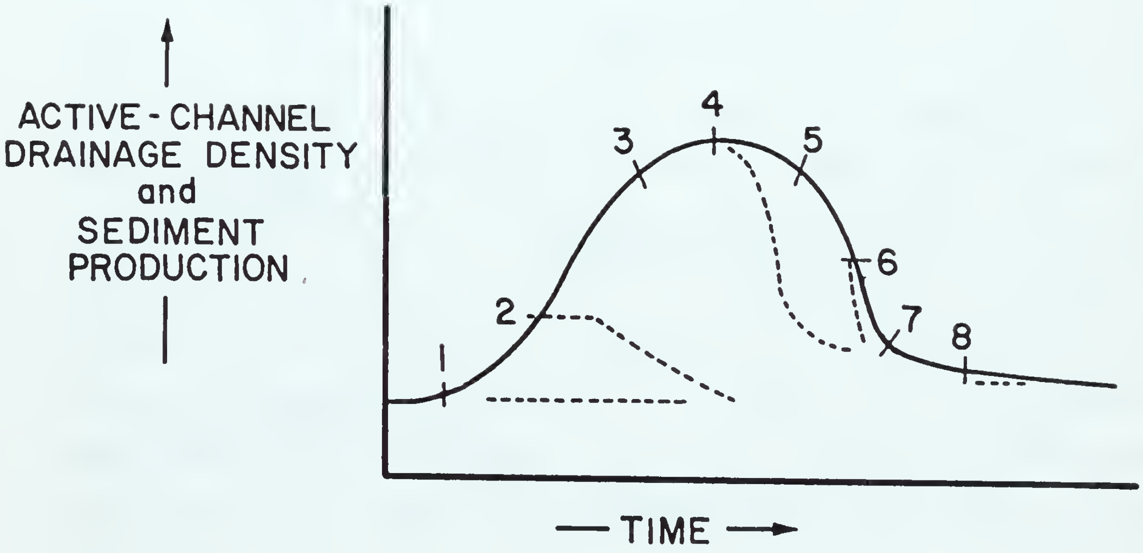


7-2 Stages of erosional evolution of South African gullies (from Schumm, 1985).

widens, until it is finally stabilized with vegetation. In Figure 7-3 a conceptual diagram shows the change in sediment yield and active channel (gully) drainage density (length of gullies per unit area) with time (see also Fig. 6-3). In a drainage basin that has been rejuvenated and in which the drainage network is incising and gullys are developing sediment production will increase, as the length of incising channels increase (Fig. 7-3, time 1 to 4). However, at time 4 maximum channel headward growth has occurred, and the channels begin to stabilize between time 4 and 7, when there is an increase in the length of channels that are relatively stable (decrease of active channel drainage density), and sediment production decreases. After time 7 the drainage basin has essentially stabilized. By understanding this cycle of channel incision and gullying from relative stability to renewed stability (Figs. 6-2; 7-2) it is possible to select times in the cycle when land management and channel and gully control practices will be most effective. For example, gullies just initiating (times 1 or 2) and gullies almost stabilized (times 6,7 or 8) will be the most easily controlled by artificial means. The efforts at times 1 and 2 will be most effective, whereas efforts at times 6 and 8 will have little effect, as the channels are stabilizing naturally. At time 4 control will be difficult and expensive. Therefore, the various stages of incised-channel evolution should be determined for Mancos-Shale channels. Also, if the causes of gully development can be determined then a program of prevention may be possible, which would be the most efficient way to approach the incised-channel erosion problem.

Clearly geomorphic landform mapping, identification of geomorphic thresholds, and analysis of landform evolution will provide valuable information that can be used to resolve the problems of reducing sediment and salt production in the Upper Colorado River Basin.

This report has concentrated on the research carried out in the low desert area of the Upper Colorado River Basin; nevertheless, Mancos Shale crops out at high altitudes where vegetational cover is greater. There is a significant decrease of drainage density with increased precipitation at higher altitudes (Eccker, 1984), as the erosional characteristics of the Mancos-Shale varies with vegetational cover.



7-3 Hypothetical change of sediment production and active channel (gully) drainage density with time. Dashed lines indicate effect of gully-control structures at various times during channel evolution (from Schumm, 1985).

Even at the low altitudes vegetational cover varies, and this is very important with regard to both sediment yield and salinity (Fig. 5-3). Bransen and Owen (1970) established a relation between the percentage of bare soil (BS), relief-length ratio (R) and sediment yield (SY) for the Badger Wash basin as follows:

$$SY = 40.87\ R + 0.03\ BS - 1.27\ (r = 0.86)$$

This indicates that quantitative relations between geomorphology, plant cover, sediment yield and salt production can be established for the Mancos-Shale terrain.

There have been significant changes in the TDS and suspended sediment load of the Colorado River with time (Hadley 1974, see Schumm 1977, p. 326). It is possible that these changes reflect long term adjustments of major tributaries to the Colorado River with the construction of new flood plains and storage of sediment in their valleys. Such natural aggradation, perhaps accelerated by the invasion of salt cedar, could prevent further channelized erosion of Mancos-Shale bedrock and therefore, it may be an explanation of reduced sediment and salt production. A regional study should be initiated in order to test this hypothesis, which if proved correct, could lead to a significant improvement of the understanding of Colorado River salinity and, in turn, the development of methods to enhance the natural storage process.

Most of the experiments performed on Mancos Shale with the exception of Lusby's (1977) were limited to a narrow range of landform types, and they were performed only during a brief period of time. It has been demonstrated that slope inclination and the seasonal changes of soil characteristics significantly affect hydrologic conditions and sediment yield on the Mancos Shale. Therefore, salt production is also dependent on these variables. In order to obtain the necessary understanding of Mancos Shale erosion and runoff processes, the experiments should be repeated for a range of slope conditions, at least twice during the spring and fall of the year, when soil characteristics are markedly different.

Clearly, additional research is needed not only in order to resolve the differences between the different research groups but also to provide badly needed information on the morphology and erosional character of the Mancos-Shale terrain. The following are very brief suggestions for future work.

1) Determine the extent of the main landform classes (badland, pediments, valley floors) by using Johnson's (1982) mapping technique (Fig. 3-3). This undoubtedly will be refined as the work progresses in order to identify the areas of high sediment and salt production.
2) Determine the distribution of incised channels and attempt to develop a means of identifying threshold conditions of valley stability (Fig. 6-1). This may permit preventive conservation in some areas.
3) For incised channels and other eroding landforms, attempt to identify the stages of landform adjustment (Fig 6-2, 7-3). This will aid in the determination of the need for conservation efforts and of the type of work required.
4) The long and short term variability of sediment loads and salinity in the Colorado River and its tributaries should be explained. A survey of valley-floor conditions at present for comparison with those of the past should be undertaken in order to determine if sediment storage in tributary valleys is causing a slow decrease of sediment and salt delivery to the Colorado River. Much of this work could be accomplished by comparison of aerial photographs.
5) The various experiments related to the effect of tracking and hillslope erosion should be repeated under the different conditions that occur during the year (Fig. 5-17). During the spring, when the surface of Mancos Shale is loose, the effect of land use on runoff, sediment, and salt yields will be very different than during periods of low infiltration capacity.
6) The various land conservation practices used on the Mancos-Shale terrain should be evaluated as far as possible by sampling sediments trapped in dams, gulley plugs, terraces, pits and furrows. This will provide information on sediment and salt storage, which, in turn, will provide the basis for an economic evaluation of the various erosion control techniques.

An expansion of the research effort is required in order to provide a firm basis for decisions regarding salinity control from diffuse sources in the Colorado River drainage basin. The Mancos Shale is only one of several salt contributing lithologic units, but the development of an understanding of sediment and salt delivery from Mancos-Shale hillslopes and valley floors can be used to develop a better understanding of diffuse-source-salinity problems elsewhere.

References

Achterberg, D. G., 1981, Laboratory study, runoff, sediment transport, and salt loading under simulated rainfall: M.Sc., Colorado State University, Fort Collins, Colorado.

Alexander, E. B., 1985, Rates of soil formation from bedrock or consolidated sediments: Physical Geography, v. 6, n. 1, pp.25-42.

American Geological Institute, 1976, Dictionary of Geological Terms: Anchor Press/Doubleday, Garden City, New York, 472 pp.

Ayers, R. S. and Westcot, D. E., 1976, Water quality for agriculture: United Nations FAO Irrigation and Drainage Paper 29, 97 pp.

Baver, L. D., 1956, Soil Physics (3rd ed.): New York, John Wiley and Sons, 489 p.

Becket, P. H. T. and Webster, R. 1971, Soil variability: a review: Soils and Fertilizers, v. 34, n.1, pp. 1-15.

Begin, Z.B. and Schumm, S.A., 1979, Instability of alluvial valley floors: A method for its assessment: Amer. Soc. Agr. Engs., Trans., v. 22, p. 347-350.

Bhasker, R. K., Bowles, D. S., and Wagenet, R. J., 1981,. Salt efflorescence-a nonpoint source of salinity: Proc. Am. Soc. Civ. Eng. Specialty Conference, Water Forum '81, pp. 1335-1341.

Blackman, W.C., Rouse, J.V., Schillinger, G.R., and Schafer, W.H., 1973, Mineral polution in the Colorado River Basin: Jour. of Water Pollution Control Federation, v. 45, n. 7, pp. 1517-1557.

Bowles, D.S., Nezafati, H., Rao, B., Riley, J.P. and Wagenet, R.J., 1982, Salt loading from efflorescence and suspended sediments in the Price River Basin: Water Resources Planning Series, UWRL/P-82/05, 142 p.

Branson, F. A. and Owen, J. B., 1970, Plant cover runoff and sediment yield relationships on Mancos Shale in Western Colorado: Water Resources Research, v. 6, n.3, pp. 783-790.

Branson, F.A., Gifford, G.F., Renard, K.G. and Hadley, R.F., 1972, Rangeland Hydrology, Kendall/Hunt, Dubuque, 339 p.

Carroll, D., 1962, Rainwater as a chemical agent of geologic processes -a review: U.S. Geol. Survey Water Supply Paper 1535-G, 18 p.

Carter, T. E., 1980, Pediment development along the Book Cliffs, Utah: M.Sc., Colorado State University, Fort Collins, Colorado.

Casey, H. E., 1972, Salinity problems in arid lands irrigation: a literature review and selected bibliography: Unnumbered report prepared by Office of Arid Lands Studies Univ. of Arizona for U.S. Office of Water Resources Research, Water Resources Scientific Information Center.

Chebotarev, I. I., 1955, The salinity problems in the arid regions. White and Water Engineering, 10-68.

Chilingar, G. V., 1956, Durov's classification of natural waters and chemical composition of atmospheric precipitation in USSR: a review: Trans. Amer. Geophys. Union, v. 37, p. 193-196.

Cline, A. J., Spears, C., Mehaffey, F., Kubin, E., Franklin, R., and Pachek, C., 1967, Soil survey: Delta-Montrose area, Colorado: U.S. Dept. Agr., SCS and Colo. Agr. Exp. Sta., U.S.G.P.O., Wash. D.C., 100 p.

Cook, C. W., 1974, Surface rehabilitation of land disturbances resulting from oil shale development: Colo. State Univ. Env. Res. Center Tech. Rpt. Series, 1, 255 p.

Craig, J. R., 1970, Saline waters: genesis and relationship to sediments and host rocks: in Groundwater Salinity, a symposium at the forty-sixth annual meeting of the Southwestern and Rocky Mtn. Div. of the Amer. Assoc. for the Advancement of Science, arranged by Robert B. Mattox, April 23-24, 1970, Las Vegas, New Mexico.

Dreibelbis, F. R, 1949, Some influences of frost penetration on the hydrology of small watersheds, Trans. Am. Geophys. Union, v. 30, p. 279-282.

Eccker, S.L., 1984, The effect of lithology and climate on the morphology of drainage basins in northwesterm Colorado: Completion Report 131, Colorado Water Resources Research Inst., Colorado State Univ., 124 p.

Enck, E. D., 1981, Non-point source salt loading from West Salt Creek near Mack, Colorado: unpubl. master's thesis Colorado State University, Fort Collins, Colorado.

Evans, R. G., Walker, W. R., and Skogerboe, G. V., 1981, Optimizing salinity control for the Upper Colorado River Basin: Report to U.S. Env. Res. Lab., Ada, Oklahoma by Colorado State Univ. Dept. of Agr. and Chem. Eng., Rpt AER80-81RGE-WRW-GVS1, 295 p.

Fisher, D. J., Erdmann, C. E., and Reeside, J. B. Jr., 1961, Cretaceous and tertiary formations of the Book Cliffs, Carbon, Emery and Grand Counties, Utah and Garfield and Mesa Counties, Colorado: U.S. Geological Survey Professional Paper 332, 80 pp.

Garrels, R. M. and Thompson, M. E., 1962, A chemical model for seawater at 25°C and one atmosphere total pressure: Am. Jour. of Sci., v. 360, p. 57-66.

Geraghty, J. J., Miller, D. W., Van Der Leeden, F. and Troise, F. L., 1973, Water Atlas of the United States: Water Information Center, NY, 95 p.

Gifford, G. F., 1972, Infiltration rate and sediment production trends on a plowed big sagebrush site: Jour. Range Management, v. 25, p. 365-366.

Gorham, E., 1961, Factors influencing supply of major ions to inland waters with special reference to the atmosphere: Geol. Soc. Amer. Bull., v. 72, p. 795-840.

Hadley, R.F., 1972, Sediment yield and land use in the southwest United States: Internat. Assoc. Sci. Hydrology, pub. 113, p. 96-98.

Hadley, R. F. and Lusby, G. C., 1967, Runoff and erosion resulting from a high-intensity thunderstorm near Mack, western Colorado: Water Res. Research, v. 3, p. 139-143.

Hadley, R. F., and Schumm, S. A., 1961, Sediment sources and drainage basin characteristics in upper Cheyenne River basin: U.S. Geol. Surv. Water-Supply Paper 1531-B, p. 137-196.

Hadley, R. F. and Toy, T. J., 1977, Relation of surficial erosion on hillslopes to profile geometry: U.S. Geol. Survey. Jour. Research v. 5, p. 487-490.

Harvey, M. D., Watson, C. C., and Schumm, S. A., 1985, Gully erosion: Bureau of Land Management Tech. Note 366, 181 p.

Hawkins, R.H., Gifford, G.F., and Jurinak, J.J., 1977, Effects of land processes on the salinity of the Upper Colorado River basin: U.S. Bureau of Land Management, 2nd Utah State Univ., unpublished report, 195 p.

Heede, B. H., 1970, Morphology of gullies in the Colorado Rocky Mountains: Int. Assoc. Sci. Hydrol. Bull., v. 15, p. 79-89.

Heede, B. H., 1975, Stages of development of gullies in the west: in Present and prospective technology for predicting sediment yields and sources, U.S.D.A., Agr. Res. Serv. Rep. 4RS-S-40, p. 155-161.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water Supply Paper 1473, 363 p.

Holburt, M. B., 1977, The 1973 agreement of Colorado River salinity between the United States and Mexico: in Proc. of Nat'l. Conf. on Irrigation Return Flow Quality Management, Fort Collins, Co., p. 325-333.

Holmes, J. W., 1971, Salinity and the hydrologic cycle: in Talsma, T. and Philip, J. R. (eds.) Salinity and Water Use, MacMillan.

Horner, W. W., and Lloyd, C. L., 1940, Infiltration-capacity values as determined from a study of an eighteen month record at Edwardsville, Illinois: Trans. Am. Geophys. Union, v. 21, p. 522-541.

Horton, R. E., 1940, An approach toward a physical interpretation of infiltration capacity: Soil Sci. Soc. Proc., v. 5, p. 399-417.

Hunt, C. B., Averitt, P., and Miller, R. L., 1953, Geology and geography of the Henry Mountains region, Utah: U.S. Geol. Survey Prof. Paper 228, 239 pp.

Hunter, W. R. and Spears, C. F., 1975, Soil survey of Gunnison area, Colorado: U.S. Dept. Agr., SCS, and Colo. Agr. Exp. Sta., U.S.G.P.O., Wash. D.C., 112 p.

Iorns, W. V., Hembree, C. H., and Oakland, G. L., 1965, Water resources of the Upper Colorado River Basin--Technical Report: U.S. Geol. Survey Prof. Paper 441, 370 p.

Jackson, W.L., Bentley, R.G., Jr., and Fisher, Scott, 1984, Results of Bureau of Land Management studies on public lands in the Upper Colorado River basin: U.S. Bureau of Land Management (Denver) Tech. Note - YA-PT-84-008-4340, 54 p.

Johnson, R. K., 1982, Geomorphic and lithologic controls of difuse-source salinity, Grand Valley, Western Colorado: unpubl. Master's theses, Dept. of Earth Res., Colorado State University, Fort Collins, Colo., 99 p.

Jonez, Al R., 1984, Controlling salinity in the Colorado River Basin, the arid west : in French, R. H. (ed) Salinity in Water courses and Reservoirs, Butterworth Publishers, 622 p.

Jurinak, J. J., Whitmore, J. C., and Wagenet, R. J., 1977, Kinetics of salt release from a saline soil: Soil Sci. Soc. of Am. Jour., v. 41, n. 4, p. 721-724.

Kemper, W. D., Olsen, J., and deMoodey, C. J., 1975, Dissolution rate of gypsum in flowing water : Soil Sci. Soc. of Am. Proc., v. 39, p. 458-463.

Kircher, J. E., 1984, Dissolved solids in the Colorado River Basin: U.S. Geol. Survey Water-Supply Paper 2250, p. 74-78.

Knobel, W. V., Dandsdill, R. K., and Richardson, M. L., 1955, Soil survey of the Grand Junction area, Colorado: U.S. Dept. Agr. Soil Survey Series 1940, v. 19, 118 p.

Lane, W. L., 1975, Extraction of information on inorganic water quality: Colo. State Univ. Hydrol. Paper 73, 74 p.

Langbein, W. B., and Dawdy, D. R., 1964, Occurrence of dissolved solids in surface waters in the United States : U.S. Geol. Surv. Prof. Pap. 501-D, p. D115-D117.

Langbein, W. B., and Schumm, S. A., 1958, Yield of sediment in relation to mean annual precipitation: Trans. Am. Geophy. Union, vol. 39, no. 6, p. 1076-1084.

Laronne, J. B., 1977, Dissolution potential of surficial Mancos Shale and alluvium: unpubl. PhD Dissertation, Dept. of Earth Res., Colo. State Univ., 128 p.

Laronne, J. B., 1981, Dissolution kinetics of soluble minerals from Mancos Shale-associated alluviums: Earth Surface Processes, v. 6, p. 541-552.

Laronne, J. B. and Schumm, S. A., 1977, Evaluation of the storage of diffuse sources of salinity in the Upper Colorado River Basin: Colo. State Univ. Env. Res. Center Compl. Rpt. 79, 111 p.

Larrone, J. B. and Schumm, S. A., 1982, Soluble mineral content in surficial alluvium and associated Mancos Shale: Water Res. Bull., v. 18, n. 1, p. 27-35.

Leythaveeuser, D., 1973, Effects of weathering on organic matter in shales: Geochim. et Cosmochim. Acta, v. 37, p. 113-120.

Lusby, G.C., 1977, Determination of runoff and sediment yield by rainfall simulation : in Toy, T. J., (editor) Erosion: Research techniques, erodibility and sediment delivery: Geobooks, Norwich, U.K., p. 19-30.

Lusby, G. C., 1979, Effects of grazing on runoff and sediment yield from desert rangeland at Badger Wash in Western Colorado, 1953-73: U.S. Geol. Surv. Water-Supply Paper 1532-I, 34 p.

Lusby, G. C., and Hadley, R. F., 1967, Deposition behind low dams and barriers in the southwestern United States: Jour. of Hydrol. (New Zealand), v. 6, p. 89-105.

Lusby, G. C., Reid, V. H., and Knipe, O. D., 1971, Effects of grazing on the hydrology and biology of the Badger Wash Basin in western Colorado, 1953-1966: U.S. Geol. Survey Water Supply Paper 1532-D, 90 pp.

Lusby, G. C., Turner, G. T., Thompson, J. R. and Reid, V. H., 1963, Hydrologic and biotic characteristics of grazed and ungrazed watersheds of the Badger Wash Basin in western Colorado, 1953-1958: U.S. Geol. Survey Water Supply Paper 1532-B, 73 pp.

Malekuti, A. and Gifford, G. F., 1978, Natural vegetation as a source of diffuse salt within the Colorado River Basin: Water Res. Bull., v. 14, n.1, p. 195-205.

Mann, D., Weatherford, G., and Nichols, P., 1974, Legal-political history of water resource development in the Upper Colorado River Basin: Lake Powell Research Project Bull. 4, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA, 62 p.

Margheim, G. A., 1975, Water pollution from spent oil shale: Unpubl. PhD Dissertation, Dept. of Civ. Eng., Colo. State Univ., 132 p.

McWhorter, D. B., 1980, Reconnaissance study of leachate from a raw mined oil shale-laboratory columns: U.S. Env. Prot. Agency Rpt. EPA600/7-80-181 or NTIS PB81 129017, 53 p.

McWhorter, D. B. and Skogerboe, G. V., 1979, Potential of interflow as a salt transport mechanism-Upper Colorado River Basin: Unnumbered final report prepared for Bureau of Land Management (contract YA-512-CT6-245), Colo. State Univ., Fort Collins, CO, 70 p.

Mundorff, J. D., 1972, Reconnaissance of chemical quality of surface water and fluvial sediment in the Price River Basin, Utah: State of Utah Dept. of Nat. Res. Tech. Publ. 39, 55 p.

National Academy of Sciences and National Academy of Engineers, 1972, Water quality criteria: U.S. Environmental Protection Agency EPA-R3-73-033, 592 p.

Nelson, J. W. and Kolbe, L. A., 1912, Soil Survey of the Uncompahgre Valley area, Colorado: U.S. Dept. Agriculture Bureau of Soils, Field Operations 1910, 12th Rept., p. 1443-1489.

Nezafati, H., Bowles, D. S., and Riley, J. P., 1981, Salt release from suspended sediments in the Colorado River Basin: Water Forum '81, Am. Soc. Civ. Eng. Specialty Conf. Proc., pp. 1327-1334.

Patton, P. C., and Schumm, S. A., 1975, Gully erosion, northern Colorado, a threshold phenomenon: Geology, v. 3, p. 88-90.

Peters, N. E., 1984, Evaluation of environmental factors affecting yields of major dissolved ions of streams in NE United States: U.S. Geol. Survey Water-Supply Paper 2228, 39 p.

Price, D. and Waddell, K.M., 1972, Selected hydrologic data in the Upper Colorado River Basin: U.S. Geol. Survey Hydrol. Atlas, Invest. HA-477, 2 p.

Ponce, S. L., 1975, Examination of a nonpoint source loading function for the Mancos Shale wildlands of the Prince River Basin, Utah: unpubl. PhD Dissertation, Dept. of Civ. and Env. Eng., Utah State Univ., 177 p.

Ponce, S. L., and Hawkins, R. H., 1978, Salt pickup by overland flow in the Price River Basin, Utah: Water Resources Bulletin, v. 14, n. 5, p. 1187-1200.

Qayyum, M. A., 1961, Salt concentration gradients in soils and their effect on moisture movement and evaporation: Unpubl. M.S. Thesis, Dept. of Agronomy, Colo. State Univ., Fort Collins, CO, 70 p. (see also Qayyum and Kemper, 1962. Soil Science, v. 93, p. 333-342.

Riley, J.P., Chadwick, D.G., Jr., Dixon, L.S., James, L.D., Grenny, W.J., and Israelsen, E.K., 1982, Salt uptake in natural channels traversing Mancos Shales in the Price River Basin, Utah : Water Resources Planning Series, UWRL/P-82/02, Utah State Univ., 194 p.

Riley, J.P., Israelsen, E.K., McNeill, W.N., and Perkins, Brian, 1982, Potential of water and salt yields from surface runoff on public lands in the Price River Basin : Water Resources Planning Series, UWRL/P-82/01, Utah State Univ., 94 p.

Schafer, W.M., 1981, Book Cliffs, Utah, Soil Survey: Unpublished report, Bureau of Land Management, Denver, 61 p.

Schmehl, W. R. and McCaslin, B. D., 1973, Some properties of spent oil-shale significant to plant growth: in Hutnik, R. J. and Davis, G. (eds), Ecology and Reclamation of Devastated Land, 1:Gordon and Breach, NY, p. 27-43.

Schneider, E. D., 1975, Surficial geology of the Grand Junction-Fruita area, Mesa County, Colorado: Unpubl. M.S. Thesis, Dept. of Earth Resources, Colo. State Univ., Fort Collins, CO, 141 p.

Schumm, S. A., 1956a, Evolution of drainage systems and slopes in badlands at Perth Amboy New Jersey: Geol. Soc. Am. Bull., v. 67, p. 597-646.

Schumm, S. A., 1956b, The role of creep and rainwash on the retreat of badland slopes: Am. Jour. Sci., v. 254, p. 693-706.

Schumm, S. A., 1964, Seasonal variations of erosion rates and processes on hillslopes in Western Colorado: Zeitschrift fur Geomorph., v. 5, p. 215-238.

Schumm, S. A., 1969, A geomorphic approach to erosion control in semiarid regions: Trans. Am. Soc. Agri. Eng., v. 12, p. 60-68.

Schumm, S. A., 1977, The Fluvial System: John Wiley and Sons, 338 p.

Schumm, S. A., 1985, Geomorphic evaluation of incised channels: report submitted to Dept. of Agri. and Wat. Supply, Republic of South Africa, 20 p.

Schumm, S. A., and Hadley, R. F., 1961, Progress in the application of landform analysis in studies of semiarid erosion: U.S. Geol. Surv. Circ. 437.

Schumm, S. A., Harvey, M. D., and Watson, C. C., 1984, Incised Channels: Morphology, Dynamics, and Control: Water Resources Publications, Littleton, Colorado, 200 p.

Schumm, S. A., and Lusby, G. C., 1963, Seasonal variation of infiltration capacity and runoff on hillslopes in Western Colorado: Jour. Geophy. Res. v. 68, n. 12, p. 3655-3666.

Shen, H. W., Laronne, J. B., Enck, E. D., Sunday, G. K., Tanji, K. K., Whittig, L. D., and Biggar, J. W., 1981, Role of sediment in non-point source salt loading in the Upper Colorado River Basin: Colo. State Univ. Env. Res. Center Compl. Rpt., n. 107, 213 p.

Simmons, D.B., Li, R.M., Schall, J.D., Kimzey, J.R., Anzia, T.L., Hubbard, D.C., and Nakagawa, W., 1982, Development of small-plot rainfall simulation devices to study effects of livestock grazing on infiltration rates, runoff, sediment yields, and salinity of surface runoff from Mancos Shale-derived soils: Bureau of Land Management, Contract Number, YA-553-CTO-1069.

Stokes, W. L. and Cohenour, R. E., 1956, Geologic atlas of Utah: Utah Geol. and Miner. Survey Bull. 52, 92 p.

Strand, R. I., Boesch, B. E., and Kruse, E. G., 1981, Salinity control-the Colorado River experience: Water Forum '81, Am. Soc. Civil Eng. Specialty Conf. Proc., San Francisco, CA, pp. 543-550.

Sunday, G. D., 1979, Role of rill development in salt loading from hillslopes: M.S. Thesis, Dept. of Civil Eng., Colo. State Univ., Fort Collins, CO., 107 p.

Swenson, J., Erickson, D. T., Donaldson, K. M., and Shiozaki, J. J., 1970, Soil survey of Carbon-Emery area Utah : U.S. Dept. of Agri. Soil Conservation Service, Washington, D.C., 78 p.

Thorne, J. P., Wilson, L., Hutchings, T. B., and Swenson, J., 1967, Chemical and physical properties of soils in the Carbon-Energy area, Utah: Utah State Univ. and Utah Agr. Exp. Sta., URS39:37.

Thornthwaite, C. W., 1941, Atlas of climatic types in the United States 1900-1939: U.S. Dept. Agric. Misc. Pub. 421, 96 plates, 7 p.

Todd, D. K. 1970. The Water Encyclopedia: Water Information Center, Port Washington, NY, 559 p.

U.S. Bureau of Land Management, 1978, The effects of surface disturbance on the salinity of public lands in the upper Colorado River Basin: 1977 Status Report, 180 pp.

U.S. Bureau of Land Management, 1980, Control of salinity from point sources yielding groundwater discharge and from diffuse surface runoff in the Upper Colorado River Basin: 1978-79 Status Rpt., Denver Service Center, Division of Special Studies, unnumbered, 37 p.

U.S. Bureau of Land Management, 1985, 50 years of Public Land Management, Washington, D.C., 27 p.

U.S. Bureau of Reclamation, 1974, Colorado River water quality improvement program: U.S. Dept. of Interior, 125 p.

U.S. Bureau of Reclamation, 1976, Glenwood-Dotsero Springs unit, Colorado preliminary appraisal report-Colorado River Water Quality Improvement Program: Salt Lake City, Utah, 32 p.

U.S. Department of Agriculture, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Agricultural Handbook No. 60, 160 p.

U.S. Public Health Service, 1962, Drinking water standards : U.S. Public Health Service Publ. 956.

Van Haveren, B.P. and Jackson, W.L., 1986, Concepts in stream riparian rehabilitation: Paper presented at American Wildlife and Natural Resources Conf., Reno, Nev.

Wagenet, R. J. and Jurinak, J. J., 1978, Spatial variability of soluble salt content in a Mancos Shale watershed: Soil Sci. v. 126, n. 6, p. 342-349.

Ward, J. C., Margheim, G. A., and Lof, G. O. G., 1971, Water pollution potentials of spent oil shale residues: U.S. Env. Prot. Agency Water Pollution Control Res. Serv. 14030 EDB 12/71, 116 p.

Warner, J. W. and Heimes, F. J., 1979, A preliminary evaluation of groundwater contribution to salinity of streams in the Upper Colorado River Basin in Colorado and adjacent parts of Wyoming and Utah: U.S. Geological Survey contract to Bureau of Land Management. Draft.

White, R. B., 1977, Salt production from micro-channels in the Price River Basin, Utah: unpubl. M.S. Thesis, Dept. of Civ. and Env. Eng., Utah State Univ., 121 p.

Whitmore, J. C., 1976, Some aspects of the salinity of Mancos Shale and Mancos derived soils: unpubl. M.S. Thesis, Dept. of Soil Sci. and Biomet., Utah State Univ., 69 p.

Woessner, W. W., Mifflin, M. D., French, R. H., Elzeftawy, Atef, and Zimmerman, D. E., 1984, Salinity balance of the lower Virgin River basin, Nevada and Arizona: in French, R. H. (ed.), 1984, Salinity in watercourses and reservoirs, proceedings of the 1983 international symposium on state-of-the-art control of salinity, July 13-15, 1985, Salt Lake City, Utah, Butterworth Publishers, p. 145-156.

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